CRANFIELD UNIVERSITY

JAN STAHL

Development of a Methodology for Joining Technology Selection based on Cost Information in the Preliminary Automotive Body-in-White Product Development Process

SCHOOL OF APPLIED SCIENCES

PhD THESIS

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SUPERVISOR: DR VALENTIN VITANOV

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Abstract

The substantial demand of the customer for the conservation of natural resources and of the environment puts pressure on the automotive industry to reduce fuel consumption and emissions. One response to this challenge is to reduce car body weight. Hence car body development has shown an increase in the use of light weight materials that demand new production methods and joining technologies. Accordingly car body engineers have progressively less time to assess the manufacturing cost of an increasing number of new design concepts with new material and corresponding joining techniques.

A review of the pertinent literature shows that there is no established methodology enabling automotive body engineers to make a rough manufacturing cost estimate of different new design concepts in the early phase of the Product Development Process.

The aim of the present thesis is to provide car body engineers with a cost estimating methodology that makes it possible for them in the preliminary phase of the design process to estimate the manufacturing cost of new design concepts more systematically, hence more reliably, thus enhancing cost reduction.

The methodology is based on the notion of Standardised Working Contents, which, as fundamental units of work, enable designers to compare the financial requirements of various new design options with greater facility and greater accuracy. Furthermore the methodology identifies the most cost efficient Joining Technique combination with a high degree of reliability.

Economical and technical data required for the methodology are gathered from an industrial survey in collaboration with the design, planning, finance and manufacturing departments of a leading automotive company.

Dynamic Programming taken from the area of Operations Research is employed to provide the optimal Joining Technique combination in terms of manufacturing cost of the car body design concept under scrutiny.

Results obtained from an automotive industrial case study confirm the effectiveness of the methodology while pointing out its limitations and possibilities.

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Abbreviations

ABC	**A**ctivity **b**ased **C**osting
BIW	**B**ody-**in**-**W**hite
BMW	**B**ayerische **M**otoren **W**erke
CAD	**C**omputer **A**ided **D**esign
CoC	**C**entre **of** **C**ompetence
CBP	**C**apital **B**udgeting **P**roblem
CBR	**C**ase **B**ased **Re**asoning
CER	**C**ost **E**stimating **R**elationship
DIN	**D**eutsche **I**ndustrie **N**orm (German Industrial Norm)
DP	**D**ynamic **P**rogramming
DTC	**D**esign **to** **C**ost
FBC	**F**eature **b**ased **C**osting
JS	**J**oining **S**ide
JSC	**J**oining **S**ide **C**oefficient
JT	**J**oining **T**echnique
JT's	**J**oining **T**echnique**s**
JTSP	**J**oining **T**echnique **S**election **P**roblem
JTSM	**J**oining **T**echnique **S**election **M**ethodology
LP	**L**inear **P**rogramming
MAG	**M**etal **A**ctive **G**as welding
MIG	**M**etal **I**nert **G**as welding
MIS	**M**anagement **I**nformation **S**ystem
MODI	**Mo**dified **D**istribution method
NN	**N**eural **N**etwork
OR	**O**perational **R**esearch
PCE	**P**arametric **C**ost **E**stimating
PDP	**P**roduct **D**evelopment **P**rocess
SOP	**S**tart **of** **p**roduction
SWC	**S**tandardised **W**orking **C**ontent

SWCC	**S**tandardised **W**orking **C**ontent **C**oefficient
TER	**T**ime **E**stimating **R**elationship
TP	**T**ransportation **P**roblem
VAM	**V**ogel **A**dvanced Start **M**ethod
VDI	**V**erein **D**eutscher **I**ngenieure (Association of German Engineers)
WC	**W**orking **C**ontent
WCC	**W**orking **C**ontent **C**oefficient
WIG	**W**olfram **I**nert **G**as welding

1 Introduction

1.1 Background

The development of new products has become a focal point of industrial competition. For senior managers around the world, developing better products faster, more efficiently and more effectively is at the top of the competitive agenda [Elliot, Wright and Saunders, 1998]. Evidence is mounting that effective design and development of new products have a significant impact on cost, quality, customer satisfaction and competitive advantage [Ullman, 1992].

Ehrlenspiel *et al.* [2006] states that a project to develop a new car is extremely complex and long lived; it may involve hundreds even thousands of people over many years. Planning and design are complicated by changing markets, long lead times and a multiplicity of choices. Engineering complexities include the numbers of parts and components, high levels of cost and quality, the number of competing objectives and ambiguity inherent in customers' product evaluation. These characteristics make the development of a new car a fascinating arena in which to study the management of product development [Urban and Hauser, 1993].

1.2 The Original Problem

The increasing use of advanced composites in the automotive industry has led to the development of new methods and equipment for manufacturing these new materials and structures. In this relatively new field of design estimating the cost of new design concepts is becoming a more complex affair; at the same time pressure is mounting to shorten the process of product development [Ehrlenspiel, 2006]. Consequently cost management plays an ever-increasing role: expenses must be controlled so that profit expectations can be met. Hence, there is a demand for methods of estimation that can provide information on product cost as early and as quickly as possible. Existing cost estimation techniques cannot fulfil these new requirements especially in the Preliminary Work Phase of the automotive Product Development Process where the correct choice of new design concepts is of critical importance.

In car body engineering, known as Body-in-White design, designers do not have at their disposal a method for assessing manufacturing costs of various new Body-in-White design options. At present, this is a time consuming procedure involving a high number of iterations that may take up to several months and relies on input from the design, planning and finance departments. According to Nißl and Lindemann [2004] the lack of data affecting the current manual process often leads to erroneous estimates of design cost, which results in lost opportunities or unexpected expenses. If there is a change in design, the cost of resultant changes in activities and resources has to be identified manually so that the project's design remains within budget [Hutterer, 2004]. Staub-French *et al*. [2002] state that without automated support to customise cost information, Body-in-White designers often employ ad-hoc methods that are prone to error.

1.3 Research Problem

1.3.1 Research Aim

The aim of this research is to develop a methodology that will enable Body-in-White designers (or managers) to compare the manufacturing costs of different new design concepts more systematically, hence more reliably, thus enhancing cost reduction in the Early Phase of the Product Development Process. The purpose is not to provide a method for calculating accurately the manufacturing cost of the product as a whole, but to provide engineers with a good method for estimating the relative cost of various design options in the Preliminary Work Phase.

1.3.2 Research Hypothesis

The research will proceed on the assumption is that it is possible to develop a methodology for estimating the relative manufacturing costs of different Body-in-White design concepts on the basis of information contained in the specification data of the new design concepts.

1.3.3 Research Objectives

The primary objective of the present study is to realise the above stated aim by developing a procedure for identifying the optimal combination of Joining Techniques for a Body-in-White design concept.

The subordinate objectives are the following:

1. To develop a definition of the Body-in-White Working Content as the mathematical unit for the above mentioned procedure.
2. To establish a mathematically definable connection between Working Contents and Joining Techniques.
3. To collect raw data and put them into a form that will make them serviceable for the development of the methodology sought.

1.3.4 Research Scope

If the research project is to meet time requirements of the research project the following strictures will be observed. The study is addressed to the work of Body-in-White designers of the automotive industry. The aim of the research is to provide them with a method of Body-in-white cost estimation, not a method of cost calculation. It is intended to compare the cost of various new Body-in-White design concepts in the preliminary phase of the Product Development Process by finding the optimal combination of Joining Techniques. This methodology is not designed to replace the later process of cost calculation in the Product Development Phases. The domain is confined to automotive companies with a large production range of Body-in-White units.

1.4 Thesis Outline

This thesis is organised as follows. In Chapter 2, a literature review takes stock of the various topics relevant to the research. There is a discussion of the importance of cost management and of various approaches for cost estimation and calculation. The Product Development Process as a whole is outlined, with special attention given to interaction between Design, Planning and Finance in the Early Phase.

Chapter 3 describes pertinent research methodologies with their techniques of data collection; on this basis a research strategy for the subsequent study is worked out.

In Chapter 4, an industrial survey is conducted by means of data collection techniques. This survey investigates and evaluates information pertinent to the development of sheets, templates, matrixes and tables required for the development of a cost estimating methodology based on optimal Joining Technique selection.

In Chapter 5, an algorithm is formulated on the basis of the Body-in-White joining process. From this is derived a cost estimation methodology comprising all data and results pertinent to the research problem.

Chapter 6 provides an evaluation of the cost estimation methodology by means of its application to an industrial case study.

Chapter 7 gives a discussion of the research results, followed by the contribution to knowledge. There is then a discussion of the conclusions which considers and validates the research aim, the hypothesis and the objectives. Finally, limitations of the methodology and possible avenues for further research are pointed out.

1.4.1 Structure of the Report

The structure of the report is presented in diagrammatical form in Figure 1.1 This diagram should help the reader follow the structure of the thesis, as well as understand the logical connection of the elements of the research project and their relevance to the project as a whole.

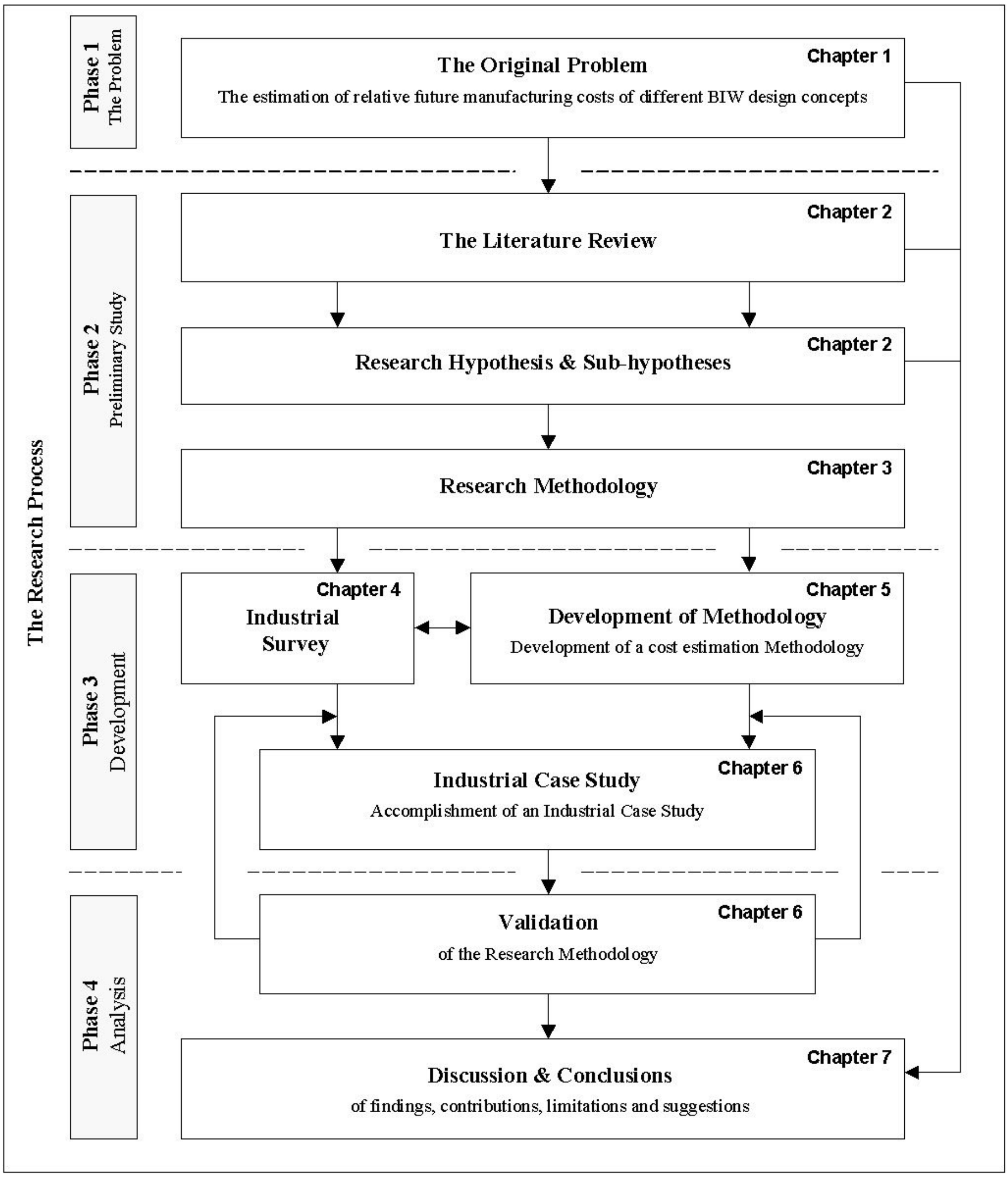


Figure 1.1: The Logical Structure of the Research Project.

2 Literature Review

2.1 Introduction

Once the research problem with its aim, objectives and scope is defined, the literature review is carried out to appraise current thinking and research on the problem of Body-in-White design and to bring together sufficient information on existing cost estimation approaches. The scope of the literature and industrial review takes in the following subject areas.

- Impact of Cost Management
- Automotive Product Development Process
- BIW Design in the Early Phase of the Product Development Process
- The application of Joining Techniques in the BIW manufacturing process
- Interaction between design, planning, finance and manufacturing departments
- Product cost structure
- Methods for cost-effective Design

The literature review has two principle purposes. First of all, it will provide the theoretical background on which the hypothesis of this research is built. Secondly, the approaches to re-engineering supply a basis for the development of a cost estimating methodology for Body-in-White design in the Early Phase of the Product Development Process.

Based on the Problem definition (see section 1.2), the review will examine

- the phases of the Product Development Process.
- the necessity of coherence in the interaction of Design, Planning and Finance
- the practical and theoretical requirements for the development of a cost estimation process to compare different Body-in-White design concepts
- The generic elements of a cost estimating process for the Body-in-White area.
- The finding of general existing cost estimation processes that are possibly applicable to the research problem.

2.2 The Role of Cost Management and a BIW designer in the Automotive Product Development Process

More than ever companies are required to gain and hold a competitive edge in their particular market sector, especially in the face of strong competition from such Low Cost Economies as China and India and their emerging counterparts in Eastern Europe [Delgado and Stockton, 2007].

The economic success of the automotive industry depends on its ability to identify the needs of customers and respond with quick development of new products that meet these needs and can be produced at low cost. According to Ulrich and Eppinger [2000], the achievement of these goals is not solely a marketing problem, nor is it a design problem or a manufacturing problem; it is a product development problem involving all of these functions. In addition to this basic conclusion Winchell [1990] asserts that cost estimating is critical to the success of any company that competes in today's marketplace. It provides information on the cost of future products. This is in contrast to cost accounting that keeps track of what current products cost. Only early and reliable cost estimation provides a company with the chance of making early improvements and modifications of their products, design and manufacturing processes. This statement is supported by Bralla [1986], who argues that the most significant cost savings can result from changes in product design rather than in production methods. Hoegh [2000] affirm that the management of cost estimation and calculation over the long period of product development is of critical importance for the success of every company that manufactures its own products.

Most people without experience in product development are astounded at how much time and money is required to develop a new product. Ulrich and Eppinger [2000] suggest that the reality is that very few products can be developed in less than one year, many require three to five years and some take as long as ten years. Ehrlenspiel *et al.* [2006] claim that a project to develop a new car is complex and long-lived; it may involve hundreds, even thousands of people over many years. These statements describe on one hand the accentuated need of cost estimating for cost management and on the other the time length and complexity of automotive product development. It shows that only companies which keep track of cost within their complex Product Development

Process are successful in today's market. Within this process the Design to Cost (DTC) moment plays an increasingly important role. The objective of DTC is to make design converge to an acceptable cost, rather than let cost converge to design [Rush and Roy, 2000]. DTC activities, during the conceptual and early design stages, determine the trade-offs between cost and performance for each of the new design concepts. DTC can effect massive savings on product cost before production begins. The approach is to set cost goals, then allocate these goals to the elements of the product. The designer must then confine his approach to the set of alternatives that are within the cost budget. According to Rush and Roy [2000], this is possible only if a tool set is developed that can be used by designers to determine the impact on cost of their decisions. The purpose of such a tool is to make enough cost information available to the designer to enable him to base decisions on it. From this it follows that DTC plays an important role in the BIW design process. The BIW designer needs a reasonable method that enables him to estimate the cost of his new BIW design concepts and to meet prescribed cost targets.

Early stage of development

According to Ehrlenspiel *et al.* [2006] of all the stages in automotive product development, the most important is the concept phase, which is called the front-end of the process. Baxter [1995] asserts that a key to success in product development is, therefore, to invest time and effort during the early stages of design to avoid having to make costly changes later. By the time detailed design is reached, most of the cost has been committed even though it is not yet spent. As a result of this pattern of cost commitment, potential cost reductions are greatest early in the design process. Another result is that the cost of making alterations increases sharply as development continues. If the design is changed at the concept stage, only sketches and models have to be revised. Wheelwright and Clark [1992] supported this statement and added that changes during production engineering can involve re-commissioning tooling at enormous cost. Proof of the importance of the early stages in the development process is that those products that were thoroughly assessed and stringently specified in early development were three times more successful than those less effectively assessed and specified.

Dertouzos *et al.* [1989] argue that the more problems are avoided in the Early Phase through careful design, the less they will have to be faced later on, when they are difficult and expensive to deal with. This conclusion has validity not only in terms of technical problems, but also in the area of failed cost management and estimation.

Swift, Raines and Booker [1997] claim that an organisation has greatest control over product cost at the early stages of the product's development - called Early Phase of development.

All these statements confirm the importance of cost estimating in the Early Phase of the Product Development Process. They identify the potential of cost reduction by estimation during the cost management process. It comes clear that it is profitable to invest time and effort during the early stages of design to detect rising product cost that will reduce the later profit for the company.

Delgado and Stockton [2007] add that for this reason cost estimations in the early stages of the product development process, when 80% to 85% of the product costs are committed, is essential. Additionally Cooper and Kaplan [1998] confirm that costs 'fixed' at the planning and design stages in product development are typically between 75% and 85%, but the costs actually incurred may be only 5 % of the total committed for the project. Also Rush and Roy [2000] showed that 70%-80% of a product cost is committed during the concept phase. Making a wrong decision at this stage is extremely costly further down the development process. Likewise Ehrlenspiel *et al.* [2000] declare that with the development of a new design concept, 70% to 85% of the technical properties - and hence costs - are fixed.

In a nutshell it is confirmed that around three-fourths of the product costs are committed in the preliminary phase of the Product Development Process. It becomes apparent that the BIW cost estimating methodology of the present research project will be required in the early stages of the design process. The coherence between the Commitment and incursion of costs during product development is illustrated in Figure 2.1.

In the beginning of the product development process the technical and economic knowledge about the new product is low but the ease of effecting technical changes is high, i.e., they are not costly. Additionally the cost incurred for design activities and the cost/technical commitments are low. In the course of time within the development process this percentage will change as represented in Figure 2.1. There arises a 'knowledge gap' between the technical and economic knowledge on one hand and the cost/technical commitment on the other. The biggest knowledge gap can be identified in the detail design and development phase of the product development. Technical and economic knowledge at that point are not sufficiently high as necessary to fill the knowledge gap. This shortcoming will be reduced in the production phase by specialists from technical Planning and Finance.

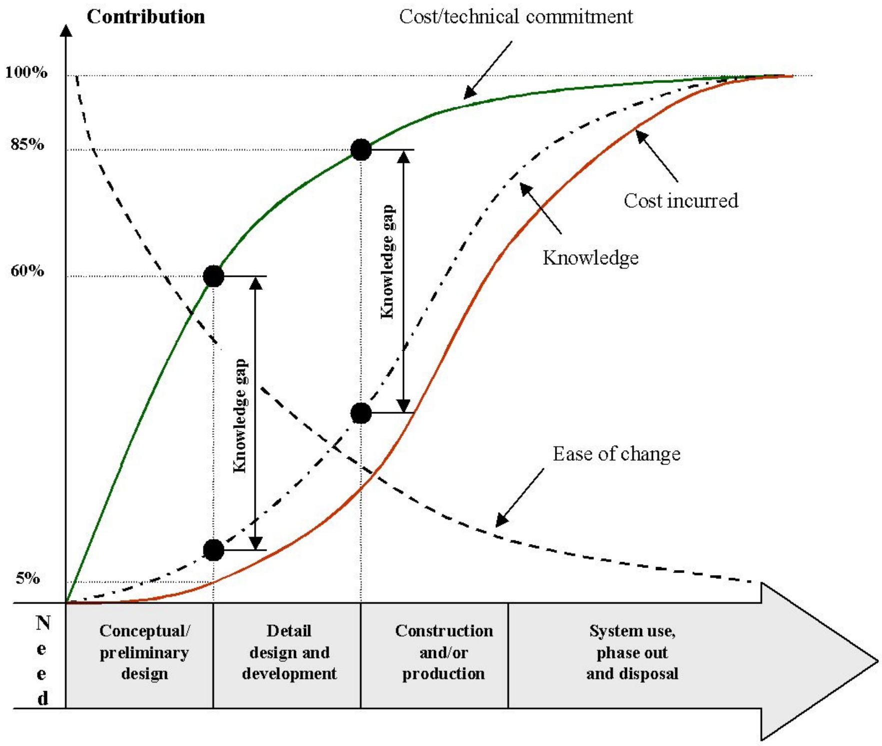


Figure 2.1: Commitment and incursion of costs during product development and the 'knowledge gap' principle [Pahl and Rieg, 1998].

The difficulties of estimating at the conceptual design phase are well recognised [Pugh, 1992; Crozier and Guenov, 1994; Meisl, 1988; Westphal and Scholz, 1997]. Rush and Roy [2000] show that the major obstacles estimators must address are:

- Limitations in the amount of available data relevant to the new development;
- Technological step changes during the life span of product development;
- The estimates need to be accurate.

Therefore estimators need company-wide co-operation and support to assist them with their decision making. With reference to the stated aim of the present research, this means primarily that the BIW cost estimating methodology is to be used by the designer in close collaboration with the planning and finance departments. This is of critical importance. In this respect the role of the BIW designer takes on an added responsibility.

2.2.1 Role of the BIW designer

As the previous investigation has shown, the biggest knowledge gap exists in the detail design and development phase, which is the domain of designers.

Craig [1992] claims that historically, designers have concerned themselves with product styling, function, quality and structural integrity but not with cost estimations or calculations. This statement sheds light on the fact that the greatest knowledge gap affects precisely that phase in which the operatives are mostly designers. Similarly, Welch and Dixon [1992] make a case for the primary tasks of a designer, which are driving factors in determining the 'time to market' of products. Kelkar [2001] adds that the designer has the great responsibility of ensuring that the product will conform to customer requirements, comply with specifications, ensure quality and reliability in every aspect of the product's use; and all these goals have to be met within a highly compressed time frame. Shetty [2002] claims that designing a product involves a constant decision-making process that includes problem solving in a sequential fashion and analysis of constraints at each step. As far as quality is concerned, the designer must aim to achieve the standards demanded by the specification; these, furthermore, must lie within the capabilities of the production department. According to Oakley [1993], many designers have practical experience with production and fully understand the capabilities and limitations within which they must work. Unfortunately, there are also many who do not.

These comments give a general idea of how extensive the area of a designer's tasks and responsibilities is. Primary the designer is well trained to deal with technical problems and to find their solutions on the basis of product specifications. So the designer may state precise requirements on the weight, stiffness, material, reliability etc. of the product, but can make practically no accurate statement about the cost of its development and manufacturing. Furthermore the increasing sophistication and variety of product functions and consumer values have made design work more complicated. However, if there is no balance between design factors, such as safety, aesthetics, ergonomics etc. and costs, the product may fail. Therefore, as Ichida [1996] observes, high performance in the area of early product cost estimating should ultimately lead to economic success.

In the case of BIW development, which is the spearhead of vehicle development process, the designer has to make a great number of decisions upon which subsequent developments like chassis, engine, interior and exterior are to depend. Technical changes or substantial modifications involve extensive and costly re-working in subsequent phases. This points clearly to the necessity of a methodology or tool that can bundle information in such a way as to permit cost estimates of new BIW design concepts. Furthermore it is of critical importance that the BIW designer be able to apply the cost estimating methodology at any time and independently of other departments involved in the Product Development Process.

2.3 Vehicle Product Development Process

In the following the vehicle Product Development Process is described in detail to reveal the tasks of departments dependent on time for successful product development. This step is important for the understanding in which phase of the Product Development Process the cost estimating methodology will be applied. Subsequently the general process of Body-in-White design with its contribution to total car cost is presented. The demand of new Joining Techniques is pointed out and a general overview of the major joining processes is given.

2.3.1 A generic Vehicle Product Development Process

Companies need a systematic Product Development Process that must be communicated to the participants. The actual process by which product designers implement their tasks and responsibilities are typically a function of the individuals involved. Their approaches, degree of documentation and habits are unique and randomly acquired. Hence, it is sometimes difficult for one person to follow up another's work without being familiar with design philosophy and approach of the former.

A clearly defined and well-organised PDP lies at the heart of an effective engineering environment; yet only a few companies have realised the potential advantages it offers. If improvements are to be made, the process has to be analysed and understood in detail.

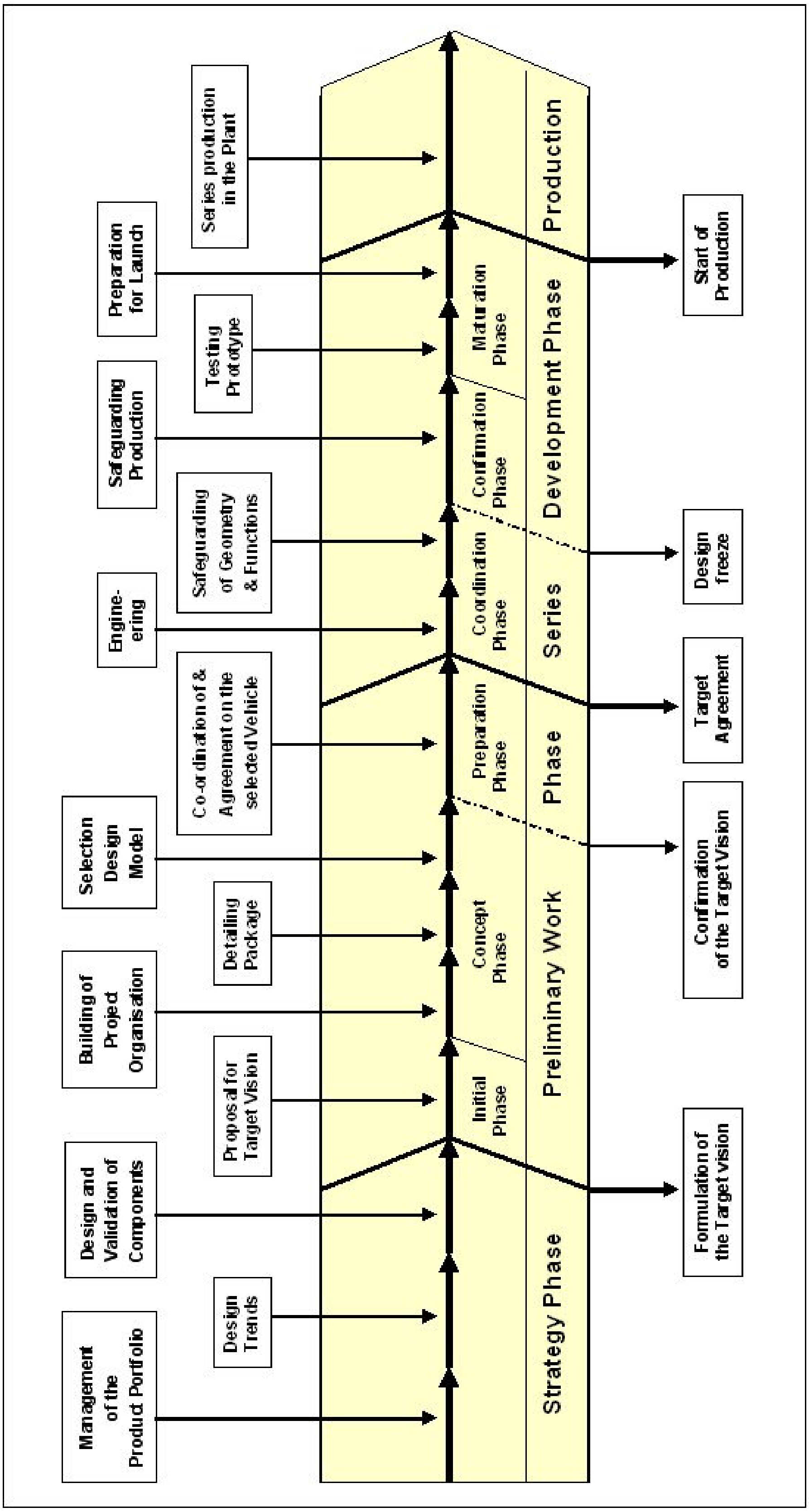


Figure 2.2: A generic automotive Product Development Process.

A new, fast, low-cost process has to be defined and then implemented. Probably many existing tasks have to be removed and some new ones added. According to Shetty [2002], overall organisation of the process changes significantly.

A PDP is the sequence of steps or activities an enterprise employs to conceive design and commercialise a product. Many of these steps and activities are intellectual and organisational rather than physical. Most automotive companies define and follow a precise and detailed PDP, while others may not even be able to describe their processes. Furthermore, every company employs a process at least slightly different from that of every other company. In fact, the same enterprise may follow different processes for each of several different types of development projects. The generic PDP of the automotive industries consists of three main phases with particular sub-phases as illustrated in Figure 2.2.

2.3.1.1 Strategy phase

The goal of this activity is to understand customer's needs and new design trends. The output of this step is a set of carefully constructed statements of customer needs organised in a hierarchical list with importance weightings for each need, a so-called list of target visions.

2.3.1.2 Preliminary work phase

Initial phase: The list of target visions provides a precise description of what a product has to do. They are the translation of customer needs into technical terms. Targets for the specifications are set early in the process and represent the hopes of the development team. Later these specifications are refined to be consistent with the constraints imposed by the team's choice of the product concept.

Concept phase: This phase follows the guiding principle: 'Formulation of adequate, marketable, competing vehicle concepts, and derivation of the model-orientated pre-developments and preliminary work to be synchronised with these concepts'. The parallel formulation of the commissioned vehicle concepts in competing, interdisciplinary concept teams working side by side will be the main task. The concept selection is the activity in which various product concepts are analysed and sequentially eliminated to identify the most promising concept. The process usually requires several iterations and may initiate additional concept generation and refinement. The result of this activity is usually the definition of a design trend, established on the basis of initial design models.

Preparation phase: three tasks are involved: co-ordination of and agreement on the selected vehicle concept for stable series development, resolution of target conflicts and creation of a project organisation for series development. The total selected vehicle concept must be defined in a manner sufficiently detailed to permit resolution of conflicts pertaining to target and ensure mastery of the business case; furthermore there must be planning for product innovation. When these goals are accomplished, the preparation phase is concluded by formal signature of the target agreement. At this point the project is commissioned for series production ("point of no return").

2.3.1.3 Series development phase

Coordination phase: This phase includes the complete specification of the geometry, material and tolerances of such parts as are to be unique to the product, the identification of those parts that are to be standard and a decision as to which of the latter are to be procured from suppliers. A process plan is established, and tooling is designed for each part to be fabricated within the production system.

The output of this phase is the control documentation for the product – drawings or computer files describing both the geometry of each part and the production tooling, specifications of the purchased parts, and the process plans for the fabrication and assembly of the vehicle.

Confirmation phase: This phase is for testing and refinement. It involves the construction and evaluation of multiple pre-production versions of the product. Early (alpha) prototypes are usually built with production-intent parts, i.e. parts having the same geometry and material properties as hose intended for the production version of the product, but not necessarily fabricated by means of the actual processes to be used in production.

2.3.1.4 Series production phase

In this, the so-called production ramp-up phase, individual products are made by the system devised for production. The purpose of the ramp-up is to train the work force and work out any remaining problems in the production processes. Products produced during production ramp-up are sometimes supplied to preferred customers and are carefully evaluated to identify any remaining flaws. The transition from production ramp-up to ongoing production is usually gradual.

According to Ichida [1996], the design, planning and finance departments are the three main pillars of the automotive development process. Inside this tradition, the design department makes sure that both the planning and finance divisions turn out products that strictly adhere to their drawings and specifications. The coherence between these departments is essential for successful product development and cost estimation. Hence this coherence will be investigated in a following section.

2.3.2 BIW Design in the Early Phase of the Product Development Process

General process of BIW Design

Based on the research aim to provide the BIW design with a methodology that can make the comparison of manufacturing costs of different new BIW design concepts more systematic, it is necessary to analyse the area where BIW designers do their work.

BIW engineering is one of the most extensive and complicated areas in the preliminary phase of the automotive development process. It is at the cutting edge of design. BIW is an automotive term used to designate the structural body of a vehicle.

Newman *et al.* [2002] assert that design in the automotive industry is organised somewhat differently from that found in other industries, since it shows a greater division between "design" – sometimes called "styling" – and "engineering". This statement throws light on the entire domain of the BIW development.

All major carmakers have standard departments organised around either car parts or development activities. Examples of the latter are body engineering, chassis engineering, power-train engineering, testing and manufacturing engineering. Each functional department and its subunits create and control an information asset that corresponds to a specific component or system, and a development step. Thus the organisation structure overlies the information asset map, as illustrated in Figure 2.3.

In dependence on Ansgar and Blount [1998], BIW design can be seen as a routine or variant design problem; as the same generic problem is faced over and over again, it is clearly understood what the design requirements are and what knowledge is needed, but the specific design solution and the pattern of use to which the knowledge is put are not repetitive.

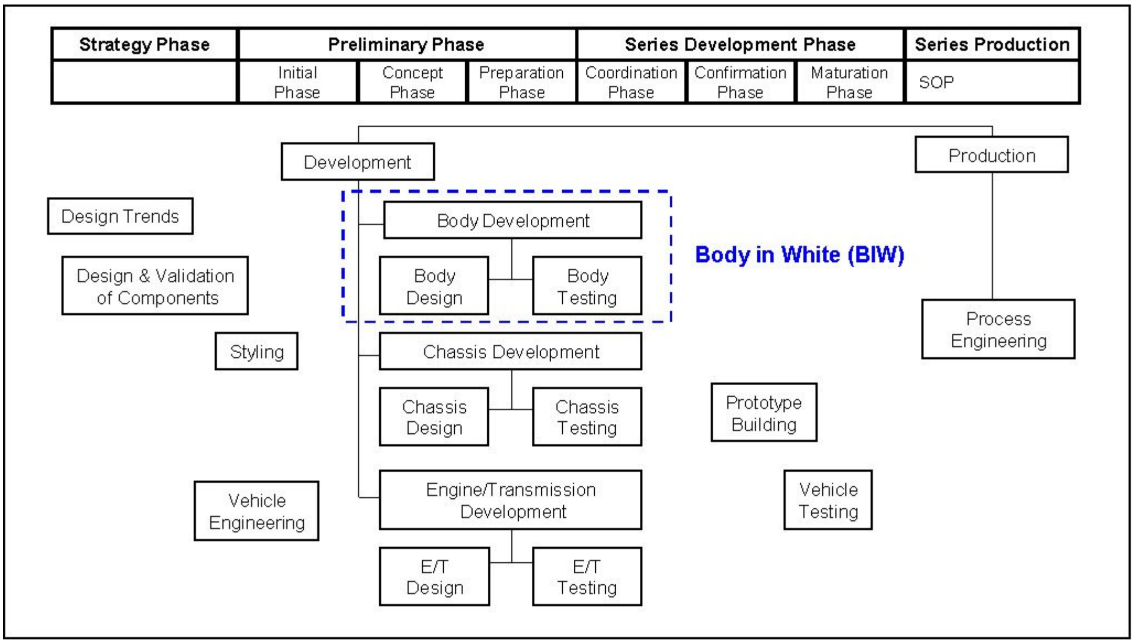


Figure 2.3: Organisational chart of development activities [Clark and Fujimoto, 1991].

Overall business driver

The literature review and the results of the later questionnaire and interviews, see section 4.3 and 4.4, substantiate the need for a method of cost estimation of BIW design concepts in the early stage of the Product Development Process. The unceasing demand of customers for more fuel-efficient vehicles makes a reduction of car body weight necessary. Hence the use of light-weight materials requiring new Joining Technologies is unavoidable. The technological change led to an increase in manufacturing cost while pertinent cost knowledge is not available. Hence the BIW engineer has no methodology enabling him to make an effective comparison of his design concepts in terms of cost in the Early Phase of development. Additionally, due to permanent shortening in product development time the designer is forced to make quick and significant decisions about his BIW design concepts in terms of cost and technical characteristics. These are the background problems that gave rise to the present research project. A methodology is needed that will enable the BIW designer to compare different BIW design concepts in terms of cost. Thus the designer will be supported by his decision making process. In addition, the designer's ability to come up with early and quick decision making - an utter impossibility under current conditions - will save development time. Likewise interaction between departments involved in BIW development process will be improved by the implementation of Working Contents. By means of this concept a technical and economic validation of design concepts is possible and will increase the exchange of important information between Design, Planning and Finance, see section 2.4.

Contribution of Body-In-White cost to total car cost

Due to the fact that BIW development belongs to the core competence of every automotive OEM it is self-evident that it takes a centre stage in the PDP. As the car body makes up the largest part of a vehicle in terms of mass, it accounts for a large part of the product cost. Hence its material and manufacturing cost is carefully monitored.

Friedrichs [2003] suggests that it is necessary to reduce material costs and to provide manufacturing technologies capable of permitting high volume production of composite components. Ungureanu [2007] adds that the major issue in today's automotive industry is the reduction of cost by the use of light weight material. This statement supports the major focus of the car industry to reach weight savings for the development of fuel-efficient vehicles. According to Stodolsky *et al.* [1995] car manufacturers know that the greatest opportunity for weight savings comes from the car body structure, where a mass reduction of up to 50% is possible [Boeman and Johnson, 2002; TECABS, 2004]. Likewise component redesign is an on-going process to reduce costs and weight of BIW components, while improving performance and reliability. In this context the appropriate assignment of material and manufacturing cost to the BIW concept turn out to be difficult and complex. DeCicco [2005] notes that manufacturing cost information is rarely reported publicly; by nature, such information is proprietary to the OEM's involved and their suppliers. BIW cost analysis projects have revealed the overall cost range of a BIW [Crow, *et al.*, 1999; Clark, 2002, Schultz, 2000]. They have shown that the production cost range of a midsize car BIW lies between 1000$ and 1600$. Likewise an estimated cost saving analysis has been carried out by [DiPietro, 2005] which indicates a savings potential of 100$ per BIW as a realistic opportunity. This savings potential is based upon actual applications currently being implemented by worldwide automotive manufactures including Fiat, Toyota, Opel, Audi, Volvo, Mercedes, BMW, Nissan and Honda. The estimate takes stock of the substitution of new material and Joining Technologies.

These statements show the proportion of BIW to total car cost. It shows the range of BIW manufacturing cost on one hand and the saving potential per BIW unit on the other. Likewise the importance of BIW development and manufacturing in connection with car body weight reduction by the use of light-weight material became apparent. Hence, the connection between materials used and their corresponding Joining Technologies is pointed out which is an essential part of the overall research project.

Current demands to the BIW design

Chapman and Pinford [2000] point out that the BIW, while representing the central and biggest single product component, has the largest influence on many of the vehicle characteristics. At present environmental legislation is forcing BIW engineers to minimise body weight, and it will continue to do so in the future [Saito *et al.*, 2000]. Shin *et al.* [2002] add that the need for reducing fuel consumption and emissions, as well as more stringent crash requirements, has led to a stiff and lightweight design for cars. As the automotive industry will continue to market new models with increased luxury, convenience, performance and safety as demanded by their customers, average vehicle weight is expected to increase. For this reason Miller *et al.* [2000] argue that weight reduction is particularly important. Likewise such safety devices as an anti-block braking system, air bags and body structure with increased safety features will involve further increases in body weight. Additionally Scamans [2007] argues that the overall reduction of the curb weight is an important and permanent aim. According to Cole *et al.* [1997] and Morita [1998] it has been taken as a rule of thumb that a weight reduction of 10% in the BIW means an improvement in fuel economy of approximately equals 5.5%. In fact, however, there is a ripple effect that must be figured into the computation. Weight reduction in the BIW enables BIW engineers to achieve similar vehicle performance with a smaller fuel tank. In conclusion, automotive materials can have an important impact on the environment. The use of lightweight materials can help reduce vehicle weight and improve fuel economy. According to Bassi *et al.* [1999], the pressure for weight reduction has resulted in a gradual decrease in the amount of steel and cast iron used in vehicles and a corresponding increase in the amount of alternative materials, especially aluminium and plastics. VDWF aktuell [2002] states that the composite of metal and plastic, the so called hybrid-technology, will continue to play a growing role in the weight reduction of the vehicle body in the automotive industry. At present the greatest scope for weight reduction in the BIW is offered by the increased use of aluminium [Pfestorf and Van Rensburg, 2006]. Recent developments have shown that a weight reduction of up to 50% in the BIW can be achieved by the substitution of aluminium for steel [Kelker *et al*., 2001]. Scott [1995] asserts that this, together with other reduction opportunities, can result in a 20–30% total vehicle weight reduction.

These remarks give a short review of the problems and tasks with which BIW designers are presently involved. Customer interest in the conservation of natural resources and of the environment on the one hand and legal regulations on the other subject the automotive industry to pressure. Reduction of fuel consumption and of emissions is of critical importance and can be achieved by reduction of vehicle weight. Lightweight construction is aimed at by all OEMs, although it is not the primary requirement [Friedrich *et al.*, 2003]. Thereby the secondary weight reduction and additional cost savings are of critical importance. Because the BIW is the biggest and heaviest part of a car, it offers the greatest scope for weight saving. Thereby it became obvious that the application of light-weight materials is one fundamental method of resolution. Hence, new and extensive body engineering tasks are a great challenge for the BIW design team in the concept stage of the PDP. The substitution of light-weight material for conventional material requires BIW design concepts of a new kind with corresponding manufacturing technologies [Faszination Stahl, 2008].

The demand of new Joining Techniques

According to Sweeney and Grunewald [2002] a variety of new materials is being used, the design team has to investigate new Joining Techniques (JT's) to optimise the process from the technical and economic point of view. The technical aspects of body engineering have to be decided upon, the aim being to determine which new technology is best suited to series production and whether it permits process reliability [Weibel, 2002; Johnson and Rudd, 2004]. The question arises whether a new JT can guarantee the same product quality attributes as former techniques in terms of stiffness, corrosion, durability, crash-test behaviour, reparability etc [Manson *et al*., 2000].

If the BIW engineer has to make a decision about which material is to be used for body development in the early stage of the design process, then a decision as to the right JT with its Working Contents (WC's) must be reached.

In the stage of the preliminary work phase where several design concepts are being investigated, any decision reached must be based on the technical terms of the WC's, see section 4.6.1.

Today, on average 20 different JT's are required for the series production of a lightweight BIW vehicle structure, Figure 2.4. In comparison with the car model's predecessor, this represents an increase in JT's of approximately 25% [Witte, 2000].

Figure 2.4: An example of the number of JT's for the BMW 5-series [Witte, 2000].

If every single application of a JT be counted as a single WC, their total number in the example of Figure 2.4 is approximately 9000. Haller [1999] assesses that from an economic point of view, the effective management of such an enormous number of WC's will, in future, be an important process within of the automotive industry. In connection with this statement Dressler [2003] makes the critical observation that while BIW designer have a large number of tools for designing a new BIW that will meet technical specifications, they have no method for estimating costs arising from the manufacture of the design concept.

These statements showed the need for a new methodology enabling BIW engineers at the early stage of development to select the design concept most efficient in terms of cost.

2.3.3 Joining Techniques for the automotive Body-in-White manufacturing

The diversity of new materials for the BIW manufacturing process requires new Joining Techniques. The interrelationship between joining material and JT's will be presented in section 4.6.2 by the elaboration of a matrix of approved Joining Techniques and material combinations.

In the following only Joining Techniques and their process description and application in BIW production are described. However, it is not of critical importance for the development of the BIW cost estimating methodology that every JT be examined in detail.

Kalpakjian [2001] admits that joining is an all-inclusive word, covering processes such as welding, soldering, brazing, mechanical fastening, and cohesiveness gluing. For many reasons, these processes are a significant and essential aspect of manufacturing operations. Joining is achieved by means of a large number of techniques. Because of the availability of the large variety of JT's, different ways of categorising the joining processes exist. From the point of view of the automotive BIW, Joining Techniques can be divided into three main categories: a) warm Joining Techniques, b) cold Joining Techniques and c) gluing. Due to the limitation of the research project, it will not be possible to consider all the Joining Technologies involved in BIW production. That is why five major representative processes have been selected and described in the following. They include JT's of category a) warm JT's: resistance spot welding, MIG welding and laser welding; of category b) cold JT's: punch-riveting, and of category c) gluing: cohesiveness gluing.

2.3.3.1 Resistance Spot Welding

Process Description

Kalpakjian [2001] affirmed that resistance spot welding has become one of the most commonly used methods of welding sheet metal. It is extensively used in the manufacture of an immense multitude of products, varying from automobile bodies to domestic appliances. Swift and Booker [2003] added that at this time, resistance welding techniques are applied to join metal sheets varying from foils, with minimum thickness of 0.3 mm, to plates, with maximum thickness of 6 mm (mild steel sheet up to 20 mm has been spot welded, but requires high currents and expensive equipment).

Resistance spot welding uses the Joule effect heating, which is produced when a welding current is conducted throughout two or more steel sheets, which often form a lap joint [Kalpakjian, 2001]. Since the resistance is highest at the sheet point of contact, most of the heat is generated there. This heat afterwards melts the material and the welding spot is formed [Tusek and Klobcar, 2004]. The parts to be joined are typically pressed together between a pair of electrodes, and an electrical current is applied to the material. The inherent resistance to the flow of current at the interface of the work pieces generates sufficient heat to melt the metals at the area of contact, forming a weld pool. When the flow of current ceases, the electrode force is maintained while the weld material rapidly cools and solidifies [ASM Handbook, 1997]. Pressure is supplied by the electrodes before, during, and after the current is applied in order to bring the work pieces into contact and confine the weld contact area at the interface [O'Brien, 1991; Gourd, 1995]. Currents range from hundreds of amperes to over one million amperes, and welding times can range from milliseconds upwards to one second [Eagar, 1992]. Resistance spot welding is suitable for joining low carbon steels, but almost any material combination can be welded using conventional welding techniques [Swift and Booker, 2003]. Spot welding is commonly used in high volume, fast welding applications. In the automotive industry, spot welding is utilised to join metal sheets of approximately 3 mm thick [EWI, 1995]. In resistance spot welding, the current applied concentrates at the point of contact of two opposing electrodes. This produces a localised bond between the metal sheets which is termed the weld nugget [Kalpakjian, 2001].

O'Brien [1991] states that during the production of spot welds, the distance between consecutive spot welds must be carefully considered. This is especially critical in automotive assembly as most of the joined components require consecutive spot welds. The minimum spacing between spot weld necessary to prevent current shunting is a function of sheet thicknesses, metal conductivity, weld nugget diameter and surface cleanliness at the work piece interface. These technical aspects of the welding process with its cycle time will be scrutinised in section 4.6.3. The ASM Handbook [1997] adds that materials for RSW electrodes should have satisfactorily high thermal conductivities and adequate low contact resistance to avoid burning of the work piece. In addition, the electrode should have sufficient strength to resist deformation operating pressures and temperatures. After a certain number of welding cycles, the electrodes must be dressed (cleaned and reshaped). [Dickinson, 1981] confirms that if the electrodes have been dressed a certain number of times, they become unable to produce quality welds and must be replaced. The number of weld cycles between dressings depends on the material properties of the sheets being joined and the welding times utilised.

Application in Automotive BIW Production

In the past resistance spot welding has been the most important joining process in the automotive industry. Almost every car model in current production has spot welding as its main joining process. The introduction of welding into automotive assembly occurred more than 80 years ago, but the advantages of spot welding demonstrate why the technique still remains the referent in the industry. O'Brien [1991] notes that from the economic point of view, it is a very economical process, suitable for both high volume and full automation, and integration with component assembly can be reached easily. The reason for its economical advantage is the fact that spot welding is a high speed process with short weld times; this makes high production rates possible. Swift and Booker [2003] add that spot welding requires fewer operator skills than alternative joining processes. The process being an industry standard is also positive accumulated experience with the technology is priceless when considering new production models. Obviously, spot welding has boundaries. The fact that the process can only be used in the joining of lap joints leads to design possibilities. Also, spot welds form permanent joints that are very complicated to disassemble for repair or maintenance activities. However, this is generally the main problem for most joining processes used in the automotive body. O'Brien [1991] remarks that spot welding requires high currents for short welding times, forcing the equipment being used as well as overloading the power line. Kalpakjian [2001] confirms that for high volume assembly, the use of resistance spot welding robots is common. Typically, articulated arm robots are used. Robots can be configured for carrying out various operations. Norrish [1992] affirms that they can also be used for replacement of manual labour in unpleasant environments or complicated operations, and are able to move much more precisely and efficiently between components and parts than a qualified welder.

2.3.3.2 Metal Inert Gas (MIG) Welding

Process Description

The Edison Welding Institute [EWI, 1997] states that arc welding processes are the most broadly employed welding technologies. They have evolved and improved significantly over the years, and continuous improvements in quality, productivity, joint life, and repair costs have taken place. Between the different arc welding processes, MIG (metal inert gas) welding has been the most developed process. The Welding Institute [TWI, 1997] reports that MIG welding is used in almost every industry sector because it is a very versatile welding technique suitable for joining both thin and thick parts, and has confirmed advantages over other arc welding processes in terms of flexibility, deposition rates, and adaptability to mechanisation.

The ASM Handbook [1997] observes that in MIG welding, the heat for fusion is established by an arc generated between a continuously fed electrode of filler metal and the work piece. The metal electrode is a metal wire, continuously fed, that melts to form the weld pool. When current is applied to the metal electrode, metal travels from the wire to the work piece through either dip or free-flight transfer modes [Norrish, 1992]. The way molten metal is transferred during MIG welding is determined by a number of factors (magnitude and type of welding current, electrode diameter and composition, shielding gas, and power supply output) and has an important influence on process performance and quality [Norrish, 1992; ASM Handbook, 1997].

The ASM Handbook [1997] explained that the two consumable, but essential elements of the MIG welding process are the electrode and the shielding gas. Consumables in MIG welding usually determine the characteristics of the joint. O'Brien [1991] adds that the chemical composition of the electrode and the shielding gas, combined with the base metal, sets the composition of the resulting weld metal, and the weld metal composition determines the joint's mechanical and chemical properties.

Swift and Booker [2003] explain that materials suitable for being joined by a MIG welding process are carbon, low alloy, and stainless steels. Most non-ferrous metals (except zinc) are also weldable: aluminium, nickel, magnesium and titanium alloys, and copper. Dissimilar materials are difficult to weld. O'Brien [1991] adds that for most MIG welding applications, the filler metal composition is very similar to the base metal. Slight modifications to the electrode composition can be made to compensate losses produced in the arc formation, or to supply deoxidation of the weld pool.

The Welding Institute [TWI, 1997] points out that the shielding gas protects the arc and weld pool from external atmosphere to avoid the formation of oxides and nitrides. Apart from the protection of the arc and weld pool, the shielding gas is necessary to form the arc plasma, and guarantee the stable transfer of molten metal from the wire to the weld pool. Commonly used shielding gases for MIG welding include argon (Ar), carbon dioxide (CO), oxygen (O), and helium (He). Typical combinations of these gases for use during steel welding are 100% CO , Ar plus 2-5% O , Ar plus 5-20 % and CO , and a trimixture of Ar, He, and CO [Gourd, 1995].

Application in Automotive BIW Production

Irving [1995] affirms that the automotive industry is the biggest market for arc welding. MIG welding is the most commonly used process in automotive assembly of all the arc welding processes. Typically, it is used for the welding of drive train members, wheel rims, structural sub-frame members, axle sub frames, axles, and various BIW components [Dickinson, 1981; Tusek and Klobcar, 2004]. The Welding Institute [TWI, 1997] confirmed that the adaptability to automation has played a decisive role in MIG welding becoming a popular process in high volume manufacturing and assembly. MIG welding also demonstrates several other advantages over alternative joining techniques. The process is suitable for almost all types of available metals and alloys. Continuous wire feed enables long welds to be deposited without stop and start, and welding can be accomplished in practically all positions (e.g. horizontal, vertical, overhead, etc.) [ASM Handbook, 1997]. Contrasting to discontinuous joining processes, MIG welding just requires access to one side of the work piece to produce a weld. O'Brien [1991] points out that in comparison with alternative arc welding technologies, MIG welding is capable of high metal deposition rates, exhibiting relatively high welding speeds from

0.2 m/min for manual welding to 15 m/min for automated setups [Swift and Booker, 2003].

Certain limitations in the use of MIG welding exist and must be considered when selecting a joining process. The ASM Handbook [1997] states that the fatigue strength of metals can be altered by the presence of weld regions. The Technical Institute [TWI, 1997] adds that the MIG welding process also faces some problems in terms of operator skill and usage, and welding equipment is more complex, and usually more costly than others. O'Brien [1991] confirms that relatively high levels of radiated heat and arc intensity can hamper operator acceptance of the process.

Norrish [1992] notes that MIG welding in automotive assembly can be operated in semiautomatic and automatic modes. Though precise placement of the welding torch and precise control of the travel speed is necessary, automation of the MIG welding process is prevalent [ASM Handbook, 1997].

2.3.3.3 Laser Welding

Process Description

According to O'Brien [1991], the use of laser processes for metal welding has experienced continuous development and expansion in industrial applications over the last 35 years. Laser welding (laser beam welding) can be found in a variety of joining applications, ranging from the sealing of electronic devices and relay containers to the forming of automotive transmissions. The ASM Handbook [1997] claims that "Laser welding uses a moving high density coherent optical energy called a laser as the source of heat". "Laser" is an acronym for "light amplification by simulated emission of radiation". Laser beams can be generated via solid state or gas medium devices. O'Brien [1991] explains that solid state lasers employ doped crystals as the lasing, or host, material, with the dopant as the active species. The dopant ion is exited by intense Krypton or xenon flash lamps [Irving, 1995]. The emitted energy, in the form of light, is reflected by mirrors within the device and then directed by additional optics to the work piece. Norrish [1992] asserts that welding takes place when the laser contacts the joint and generates adequate heat to produce the coalescence of the materials to be joined. Laser welding can be used to form deep or shallow penetration welds. O'Brien, [1991] adds that the deep penetration welding process is used for joining sheet meal thicknesses of 1-32 mm, and is the technique used in automotive body assembly.

Laser welding is appropriate for numerous joint designs and configurations. Lap joints, a common configuration in sheet metal assemblies, are weldable via the laser beam process, as are butt edge, corner and T-joints [Norrish, 1992]. For automotive applications, lap and butt welds are most commonly utilised. Before laser welding, joints must be cleaned of all contaminants, see section 4.6.3. Also, the amount of gap between component sheets must be kept within specified welding tolerances. These tolerances are dependent on sheet thickness, welding speed and beam characteristics [O'Brien, 1991]. Laser welding can be used for the joining of almost all metals. Metals can be joined to themselves or others that are compatible. The effectiveness of the laser beam and the resulting weld performance are dependent on the composition and properties of the metals being joined [O'Brien, 1991]. The ASM Handbook, [1997] points out that the available laser commonly found in automotive industrial applications are the CO_2 gas laser, the Nd: YAG (Neodymium doped, Yttrium Aluminium Garnet crystal) solid state laser, and the high power continuous-wave.

Application in Automotive BIW Production

According to O'Brien [1991], laser welding has increased its appearance in the automotive industry over the last thirty years, and the process is being accepted for a diversity of assembly applications. Several automobile manufacturers are using welding extensively in vehicle production. Hanicke [1995] claims that one of the primary driving forces behind the use of laser welding in automotive production is the fact that the process is able to produce welds with higher static and fatigue strengths, and hence improved body strength, over conventional joining processes. Laser seam welding provides high joint stiffness with very little weld distortion relative to the more common arc seam welding processes. Moerman and De Bleser [1995] assert that tighter seam welded joints are achieved through laser welding, reducing the probability of corrosion due to gaps in the seam. Another advantage is that no electrodes or filler metals are required [ASM Handbook, 1997]. The application of laser welding processes in automotive assembly has some process limitations. To obtain the desired accuracy, precise placement of the work piece is necessary. The components must be situated in such a way that the joint is exactly aligned with the point of beam contact. This degree of precision requires complex fixturing equipment. As mentioned earlier, the effectiveness of the laser welding process is highly correlated to the energy absorption properties of the metals being joined. The ASM Handbook [1997] observes that the high reflectivity and conductivity of some metals adversely affects their weldability. Jain [1997] confirms that in addition to high consumable costs, laser welding processes require relatively large capital investments in process equipment.

The ASM Handbook [1997] affirms that due to the process characteristics, laser welding requires automated equipment. The laser beam source and associated control systems requires an important investment, which is generally much higher than those of alternative joining technologies. In laser welding applications, worker safety is a major concern. The high energy beam can mean a serious hazard. Also, fumes generated during the welding of certain materials may be dangerous to operators. Stations utilising high power lasers are generally shielded to prevent any contact with the equipment during welding. Jain [1997] argues that though laser welding is highly automated and requires little direct operator skill, comprehensive workforce training is recommended and technical laser specialists are often present during each production shift.

2.3.3.4 Riveting

Process Description

Pursuant to Bokhari [1995], mechanical fastening techniques offer alternative methods for joining materials. Many mechanical fastening processes are part of the oldest joining methods used in industry, used before both resistance welding and arc welding processes. Mechanical fastening includes a wide range of techniques using threaded fasteners (e.g. nuts, bolts and screws), interlocking, clinching and riveting. Recent interest in modern riveting processes has arisen for the joining of sheet metal components. Parmley [1989] confirms that the use of rivets has been constantly expanding in assembly operations in numerous manufacturing industries, ranging from furniture to military, and appliance to automotive Industry. Additionally Parmley [1989] explains that in the self-piercing riveting process, two or more sheets can be joined by an insertion of a tubular rivet. Rivets pierce the materials to be fastened and form a permanent joint in a single operation. As such, no previously produced holes are required. The rivet is introduced into the materials by a punch press operation, the tip of which is referred to as a guide button. A shaped die, the upset die, is placed opposite the punch die on the other side of the component sheets. The shank of the rivet acts essentially as a shearing punch, cutting through the upper layers of material and partially into the lower layers until restricted by the force of the upset die. As the rivet travels into the component sheets, it displaces the materials into the bottom die. This action causes the shank of the rivet to flare outward which effectively locks the rivet into the material, forming a permanent joint [Bokhari, 1995]. Generally, the rivet does not fully pierce the lower sheet of material. As such, no slug of waste material is generated, as in alternate riveting processes [Nagy, 1994]. Self-riveting process can join most materials and combination of materials. Metals, plastics, ceramics, and wood are commonly joined [Swift and Booker, 2003]. [Parmley, 1989] states that the geometry and tolerance design of the rivets are dependent on the process parameters. Rivets, depending on material composition and the application for which they are designed, are typically heat treated to achieve the desired levels of hardness, strength and formability. Coatings are often applied to the rivets in order to achieve colour matching or to provide sufficient corrosion resistance. Parmely [1989] suggests that as in spot welding, self-piercing riveting can be employed only in the joining of lap joints. The edge and pitch distance are two key parameters that must be taken into account during the design stage in order to ensure satisfactory joint performance. The edge distance is defined as the space between the centre line of the rivet and the edge of the component sheets. For metals, the minimum edge distance should be twice the diameter of the rivet used in order to obtain sufficient bearing strength and prevent the potential buckling of the component materials. The pitch distance is defined as the spacing between the centre lines of adjacent rivets. In metals, the minimum pitch distance should be three times the rivet shank diameter in order to avoid unnecessary high stress concentration.

Application in Automotive BIW Production

According to Bokhari [1995], due to improvements over the years, industrial riveting techniques have become reliable, automated, high speed joining processes. In particular, self-piercing riveting has attracted the attention of car manufacturer due to its advantages and potential characteristics for extensive, cost effective application.

Amongst its advantages, the very short cycle times have been highlighted. Bokhari [1995] adds that the riveting cycle consists of alignment of the riveting head with the work piece, advancing of the punch, punching of the rivet, punch retracting and feeding of the next rivet. The short riveting times, added to the fact that the process is suitable to automation, allows the achievement of very high assembly speeds. Compared to common welding processes, the self-piercing technique needs much less energy. Also, the process can be used to join dissimilar materials, including both metals and non-metals. The strength of riveted joints has been demonstrated to be equivalent or ever higher than spot welded joints for some applications. Nagy [1994] claim s that self-piercing riveting requires fewer fastening points than spot welding. As riveting produces a visible connection, riveted joint quality can be determinable through visual inspection. The self-piercing riveting produces minimal heat and low levels of noise emission, providing satisfactory working conditions. The investment needed for the stabilising self-piercing technology is similar to the investment needed for spot welding and MIG welding, riveting tool life being very long [Bokhari, 1995].

When designing BIW's, designers put effort into reducing body weight as much as possible. The use of rivets in assembly processes adds extra weight to the vehicle, and consequently reduces fuel efficiency. Nagy [1994] suggests that designers must pay attention when considering riveting for the joining of appearance parts, as the method can bring surface distortions. Components designed for self-piercing riveting must also be made with somewhat wider flanges, relative to parts designed for spot welding, in order to satisfy riveting parameters. Bokhari [1995] asserts that the self riveting process is very simple and requires minimum operator skills. Robotic riveting utilises basically the same robots as are used for robotic spot welding. It has been debated that the weight of riveting system components to be mounted on the robot may be less than the weight of the spot welding equipment, thereby decreasing the necessary payload and allowing the specification of smaller robots.

2.3.3.5 Cohesiveness Gluing

Process Description

Parmely [1989] states that "Adhesives are defined as materials capable of joining parts, or adherents, together by surface attachment". O'Brien [1991] points out that nowadays many different adhesive types exist: cements, glues, pastes, organic mucilaginous compounds and synthetic, specially formulated inorganic compounds. Irving [1995] adds that the number of specific adhesive alternatives has grown significantly due to the increasing interest in adhesives in the fabrication of products. The Edison Welding Institute [EWI, 1995] claims that in the last two decades, the automotive industry has become more and more interested in investigating the viability of utilising gluing processes in automotive assembly. O'Brien [1991] states that in comparison with MIG welding, cohesiveness gluing can produce a continuous joint between parts. The continuous joint is good at distributing stresses more effectively than non-continuous joining methods such as spot welding and riveting. "Joints designed for cohesiveness gluing should be made to endure primarily tensile and shear loading, as bonded joints tend to perform weakly under peel or cleavage loadings". To form an adhesive bonded joint between metal components, a non-metallic adhesive is applied at the joining surfaces and the parts are put in contact. The adhesive needs to be sufficiently fluid to completely wet the adherent surfaces. Bonding of the metal parts takes place when the adhesive hardens dried by application of either pressure, heat, or both. Adhesive has to be applied very cautiously to ensure that the adhesive does not contract excessively and generate undesirable internal stresses. Parmely, [1989] adduces that differing from welding processes cohesiveness gluing creates a non-metallurgical bond and the surfaces joined are not melted.

The application of pressure and/or heat to the parts is required to transform the adhesive from its initial form to its final, solidified state. This process is termed as curing. Different parameters influence the curing process according to the adhesive used; curing can take place via chemical reactions or by simple solvent evaporation. Also, the process can occur at ambient or elevated temperatures. Parmely [1989] adds that the level of heat and pressure required must be accurately controlled to prevent adhesive expulsion, excessively thick bond lines and inordinately fast or slow curing.

According to [Gauthier, 1990], adhesives are listed according to functional use or chemical composition. Functional categories include holding, sealing and structural adhesives. Holding adhesives form joints between parts, but bear minimal structural loading. Sealing adhesives, such as caulking compounds, serve to exclude gases or liquids from a joint. Structural adhesives may be defined as materials used to transfer loads between adherents in the specific environments to which the components are exposed. Gauthier [1990] adds that the most widely employed chemically reactive structural adhesives are epoxies, polyurethanes, silicones, cyanoacrylates, modified acrylics, anerobics, phenolics, polymides and polybencimidasoles. Tusek and Klobcar [2004] confirm that epoxy adhesives are structural adhesives most commonly encountered in the automotive BIW production.

O'Brien [1991] claims that the main characteristics of a bond—durability and strength—are extremely dependent on the material interactions at the adhesive-adherent interface. The bond between the adhesive and the adherent surface is often the weakest point of the joint. If the contact surface does not receive correct preparation for adhesive application less satisfactory joint performance is probably obtained. According to Clearfield *et al*. [1995], various mechanical and chemical treatments can be applied as preparation of the contact surfaces. The selection of the proper treatment methods is mainly dependent on the composition and morphology of the metal surfaces. The pre-treatment processes have to remove all possible contaminants without affecting the characteristics of the adherent. After being retreated, components require careful handling. The time between surface preparation and adhesive application should be reduced to the minimum achievable.

Application in Automotive BIW Production

The application of gluing techniques is not new in automotive BIW manufacturing. Adhesives have been used in the automotive industry for the joining of non-structural and semi-structural components. Irving [1994] asserts that metal-to-metal, plastic-to-metal, and plastic-to-plastic are the common material applications. According to Tusek and Klobcar [2004], the non-structural use of bonding occurs in the attachment of carpeting, mirrors, headlights and trim. Semi-structural cohesiveness gluing applications include the hemming of doors, hoods, and deck lids, the attachment of windshields and backlights, and the joining of body panels. Beenken [2003] states that car manufacturers have realised that cohesiveness gluing processes are suitable for many different applications. Specifically, manufacturers have become interested in the application of adhesive technology, including weldbonding and rivbonding, in the metal-to-metal bonding of load-bearing, structural body components. Compared to alternative joining technologies, cohesiveness gluing introduces a number of advantages. One of the main reasons that make designers and planners interested in the cohesiveness gluing process is that it provides joints with high rigidity and stiffness. The high stiffness results because 100% joint efficiency can be achieved between joined components. Irving [1995] states that experiments have confirmed that as an average, cohesiveness gluing can increase joint stiffness by nearly 40% compared to spot welding. McCleary, [1995] assert that bonded joints also display more even load distribution and improved fatigue performance. The excellent fatigue performance of adhesive bonded joints comes from the capability of the adhesive to absorb crashes and vibrations. Sawyer [1995] adds that this ability means that vehicle NVH (noise, vibration and harshness) levels are improved. Different from other welding processes, cohesiveness gluing does not negatively affect the corrosion resistance properties of the metals joined. In fact, cohesiveness gluing decreases joint vulnerability to corrosion by creating a water-proofed barrier. Also, cohesiveness gluing is suitable for joining dissimilar materials. Another benefit of cohesiveness gluing compared to welding methods is that it is a relatively low temperature process. Curing of majority automotive adhesives can be conducted at temperatures of less than 400 F (240 C). O'Brien [1991] suggests that cohesiveness gluing also gives a better looking joint as it does not involve weld marks or rivet heads.

The application of cohesiveness gluing is attended by some limitations when applied to structural automotive components. The main one has been manufacturers' lack of confidence in the durability of bonded joints. Another limitation of cohesiveness gluing is the low performance of joints under peel loading and high temperature conditions. O'Brien [1991] states that most adhesives have operational temperature ceilings in the range of 500 F (260 C). Also, the need of preparation for the contact surface increases the number of required assembly operations and ends in higher material costs. Adhesive curing needs extra capital investment, including curing ovens and induction curing equipment. Curing processes also result in additional operations and longer manufacturing times. Finally, O'Brien [1991] adds that many adhesives degrade during exposure to extreme conditions in combination with excessive heat and humidity,

conditions usually found in an automotive BIW production. Application of adhesives in automotive BIW production can be carried out either manually or robotically. O'Brien [1991] explains that for automotive production, manual adhesive application is normally conducted with the help of dispersing guns. Robotic adhesive application is comparatively simple. Adhesive distributors, basically identical to the manual ones, are affixed to the end of the robot arm and the adhesive is supplied from a pumping system.
These descriptions of the characteristics and application of JT's in the automotive industry form a basic step leading to the consolidation of information. Section 4.6.2 to 4.6.4 will continue in the same vein.
The subsequent section attended to the interaction between departments that are involved in the BIW development process. Like it was addressed before as a business driver of the research project it is important for BIW design process to increase the exchange of important data and information between Design, Planning and Finance.

2.4 Interaction between Design, Planning and Finance

As already mentioned, coherence between the design, planning and finance departments is of particular importance for the cost estimation of future BIW design concepts. For that reason the interaction between these departments will be analyse in the following.

2.4.1 Impact of internal Process Organisation on Cost Estimating

According to Schmidt [1996] a well defined, smooth and accurate interaction between the design, planning and finance departments during the PDP is one of the most important requirements for accurate cost estimation and cost saving. This statement will be supported at length by figures and comments in the following.
Once the design department has formulated its concept, the task of the planning department is to work out in detail the production process. Becker [1988] asserts that the plan must include the development of the launch and production scenarios for the new concept. According to Bronner [1992], on the basis of this production plan the finance department must then calculate the cost of manufacturing the product. As Beitz *et al.* [1992] confirm, if this cost calculation exceeds the defined target costs of the project, the design concept must be returned to the design department for revision. Exceeding the defined target cost is a worst case scenario; it means that the design

department must come up with a completely new concept. Figure 2.5 illustrates the coherence between Design, Planning and Finance within the development process.

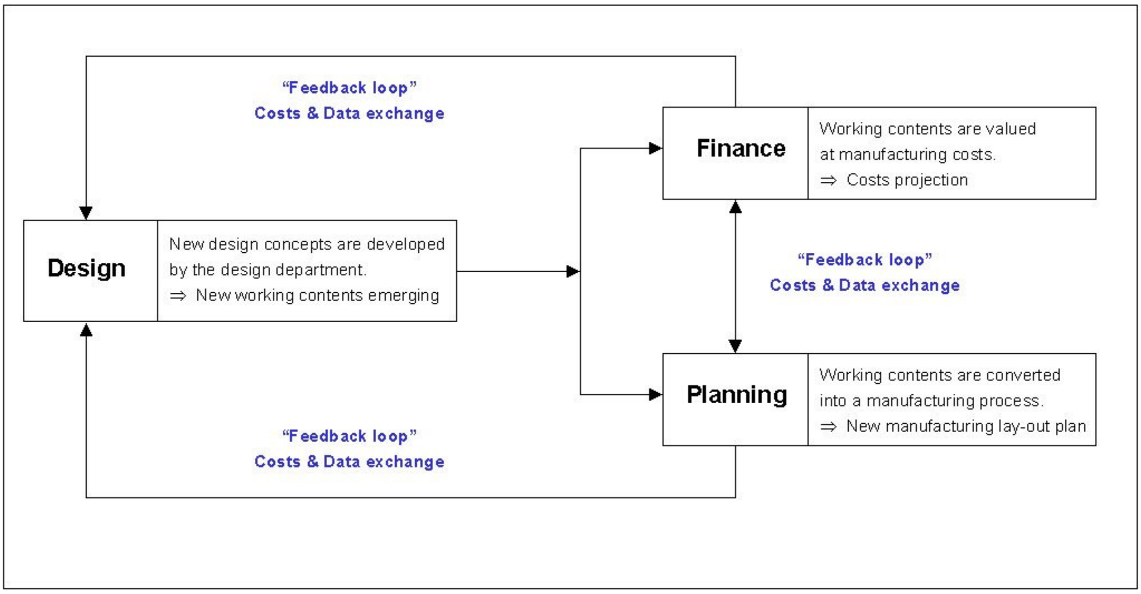


Figure 2.5: Feedback loop between Design, Planning and Finance.

2.4.2 Further development of the Loop System

As demonstrated in Figure 2.5 feedback loops are an important medium for the costs and data exchange between departments involved in the development process. According to Bock *et al.* [1990], introducing an iterative loop could improve design concepts in terms of cost. Scheer [1995] claims that repetitions along this loop could be minimised or prevented if Design were able to achieve a cost estimation for their new design concepts in the early stage of development. Pickel [1989] asserts that this early process of cost estimation is hampered by the fact that cost estimation can be achieved only with the cooperation of the design, finance and planning departments. These assertions make a contribution to the original problem of the present research work. They make clear that cost estimation at present is a lengthy procedure and requires input from Design, Planning and Finance. The organisational separation of the design, planning and finance departments has the consequence that the cycle of their interaction is time consuming. Pursuant to Scheer [1990] and Ehrlenspiel and Lindemann [2005], the current system of iteration may be called the "long" feedback loop, see Figure 2.6. "Short" feedback loop 2: Intensification of cooperation between Design, Planning and

Finance. In the "long" control loop information is provided late and is sometimes lost. Jehle [1994] argues that when this happens, revisions of the design concept are accomplished only at great additional expense. Such loss of time and money will be reduced if the feedback loop is shortened, if the "long" feedback loop is replaced by a "short" one. A "short" feedback loop is one that makes information for cost estimation available to Design in the early stage of concept designing [Fischer *et al.*, 1992], Figure 2.6.

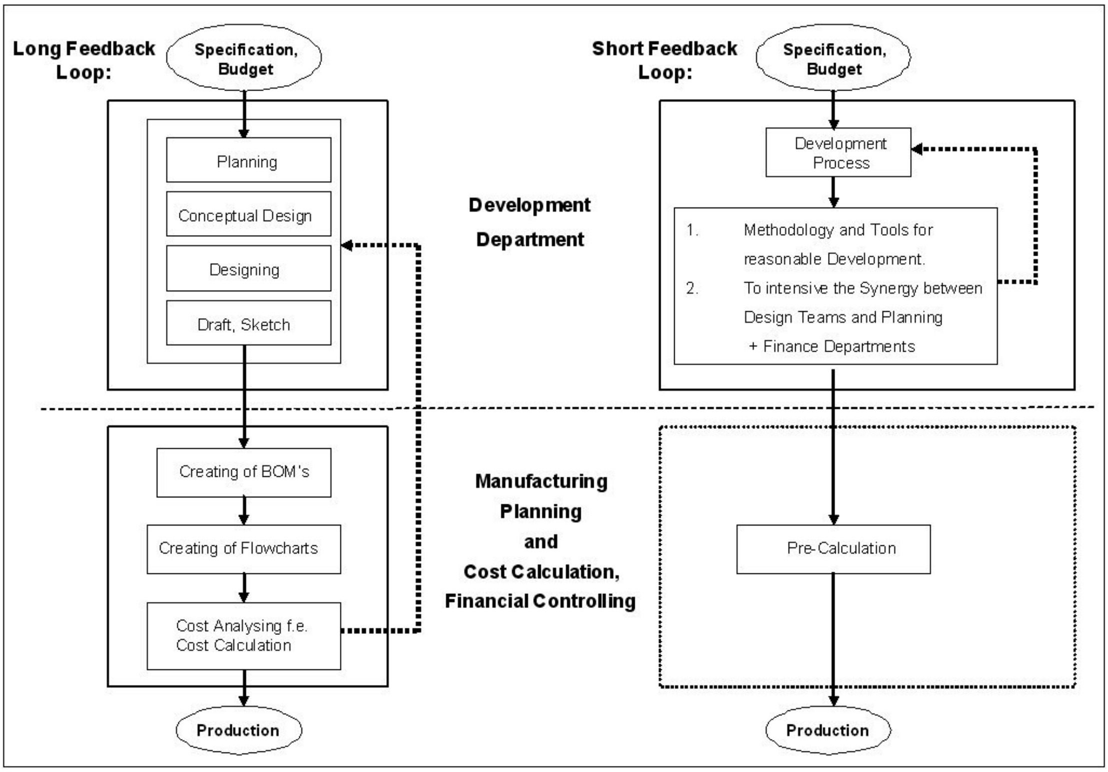


Figure 2.6: Description of cost analysis during the design process [Ehrlenspiel and Lindemann, 2005].

According to Heil [1993] a feedback loop can be considered as "short" if it satisfies three requirements:

- Application of methods for cost effective design within the design stage.
- Early provision of relevant cost information from planning and finance stages.
- Intensification of collaboration between design, planning and finance stages.

In the 'long' feedback loop cost estimation and calculation is the exclusive prerogative of Planning and Finance. Under these circumstances a designer cannot obtain accurate information about the manufacturing costs of his design without extra input from process planners and finance and plant managers. This process is lengthy. The aim of the present study is to provide the design stages with its own method for cost estimation. The aim, therefore, is to create a new "design preliminary loop" specially adapted to use by the design department, see Figure 2.7.

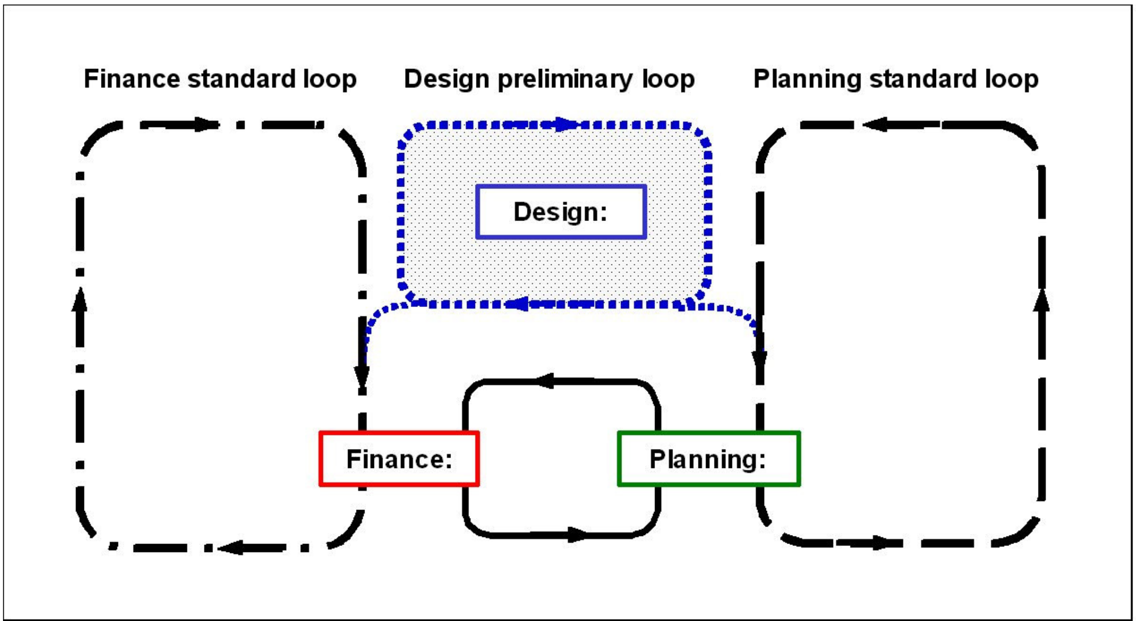


Figure 2.7: Finance, planning and design preliminary loop [Stahl, 2003].

The additional "preliminary loop" system provides the BIW design engineers with a procedure for making rough calculations and forecasting costs for their design concepts [Stahl, 2003]. Before the design department refers the new design concept to Planning and Finance, the design concept will pass through the "design preliminary loop" system for cost estimation. This will provide the BIW engineer with an opportunity to evaluate his design concepts in advance and to decide which will be best in terms of cost.

In this way a user from the design department without great practical experience with planning and finance will be in a position to obtain rapidly an estimate for different design concepts. Hence Design will acquire a disclosure of the cost savings potential early in the development process. Once a given design concept has been selected on the basis of the evaluation technique provided, it will be transferred to the standard loop, which involves Planning and Finance.

A "short" feedback loop can be achieved through the intensification of collaboration between Design and the other two departments. Pursuant to Ehrlenspiel [1992], the intensification of collaboration can resolve procedural and organisational problems that hamper early cost estimation during the design process. For the achievement of the "short" feedback loop and the supply of decision-relevant cost information a direct link-up between Design, Planning and Finance is of immeasurable importance.

2.4.3 Knowledge Domain between Design, Planning and Finance

The fact that the design, planning and the finance departments often have different perceptions of themselves and of each other constitutes a major problem that must be resolved if there is to be early cost estimation in the preliminary phase of the PDP. Only on the basis of a common point of view will participants be able to communicate their existing knowledge [Stahl, 2003].

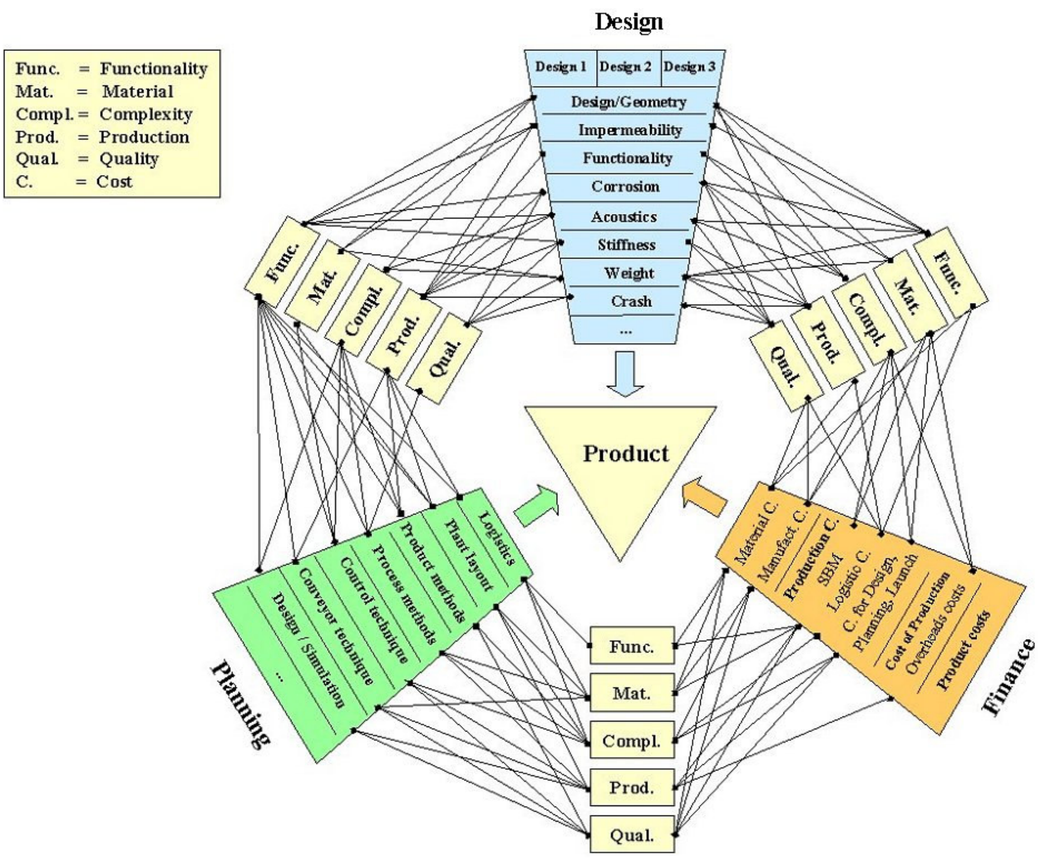


Figure 2.8: Knowledge domain between Design, Planning and Finance.

Figure 2.8 provides an illustration of the decision domain areas between departments that have been a target for knowledge acquisition and decision situation prototyping.

In analysing the complexity of the PDP and searching for common denominators between Design, Planning and Finance, one may derive advantage from generally accepted itemisations [Ehrlenspiel *et al.*, 2000] as shown in Figure 2.8.

In using these itemisations, one assigns the data pertaining to each department to such attributes as are illustrated, e.g. Functionality, Material, Complexity, Production Process and Quality [Stahl, 2003].

These attributes are used as a "link" between Design, Planning and Finance with the aim of shortening the time required for information exchange. This itemisation of knowledge increases the information made available to the design department about cost pools of WC's, but does not provide a methodology for making an early cost estimate during the design process.

The implementation of these attributes is an important move toward the intensification of collaboration between departments that are involved with the PDP. This is an auxiliary part for the development of a new cost estimation process because of systematic and transparent data exchange.

2.5 Approaches for cost effective Designing

Generally, in the past the costs of design concepts were kept apart from the designer. Consequently the designer, whose mindset was skewed towards technical functionality, tended to overlook the costs of manufacturing [Eaglesham, 1998]. Busch [1999] affirms that with the implementation of value analysis, the role of cost estimation has increased, but the attempt to retrain every designer as a cost analyst was doomed to failure. Nevertheless, second thoughts about cost-optimised design will be unavoidable in the future. For this purpose, the designer requires information that the designer can use for proper manufacturing cost estimation [Eaglesham, 1998]. Therefore it is not the objective and the task of a designer to assume the position of a planner or controller. The designer's tasks are to design and to cost out a functionally-optimised design concept. Ehrlenspiel *et al.* [2000] claim in this context the objective that for Design, cost information of design concepts provided has to be significant, manageable and not too detailed.

2.5.1 Product Costs

An understanding of the product cost structure is essential to that of the process of estimating. This structure is illustrated in Figure 2.9.

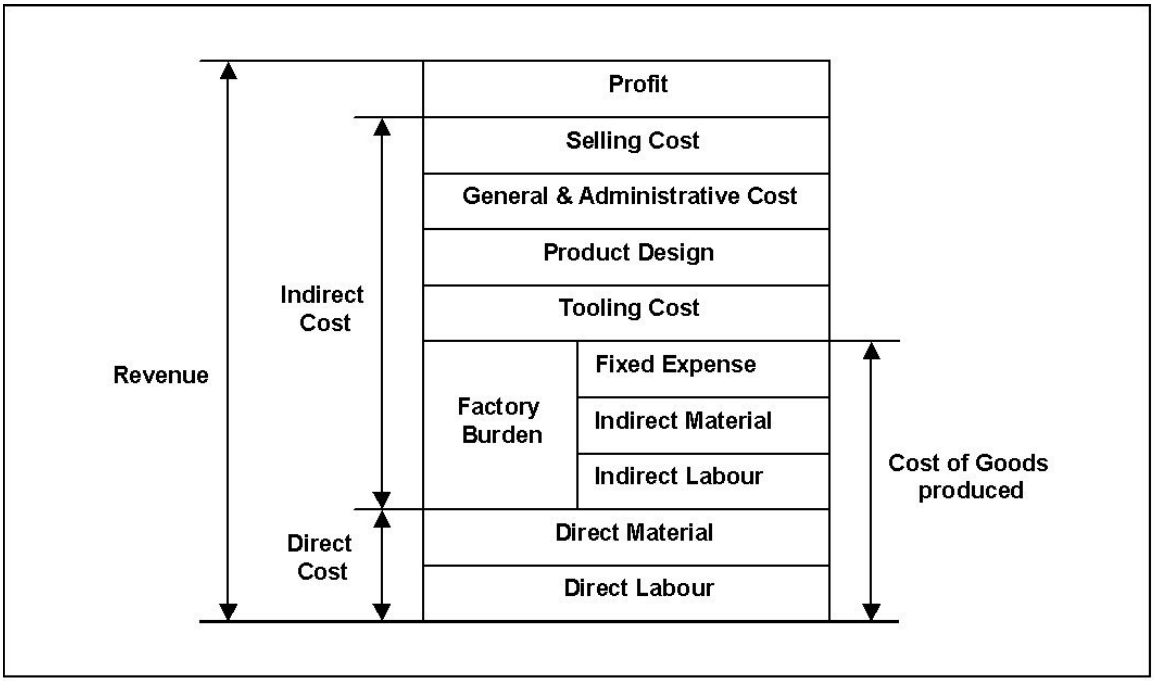


Figure 2.9: Product cost structure [Winchell, 1990].

In the cost environment of the BIW production, it is seems reasonable to ascribe 80% of the production costs for a vehicle body structure to the costs of JT's [Schrödinger, 2003]. With the primary target of aiding the body engineers in their effort to estimate the cost of vehicle body structures in the early phase of development, the focus of the research work is on the assessment of costs of JT's in the BIW area. An investigation of cost structure carried out by Finance and covering every distinct technique of joining resulted in a classification based on the distinction between investment cost and operating costs, the latter being subdivided into cost operation resources, energy costs and maintenance costs. This structure of costs will serve as a basis for later cost estimation.

2.5.2 The general Process of Cost effective Designing

For making development decisions, the product development team requires a cost-estimation tool. According to Ulrich and Eppinger [2000], such a process comprises two types of analysis: the *quantitative* and the *qualitative*. The emphasis of the process is on a quick, approximate methodology for supporting decision making within the product development team.

With the instability of existing information and data, which are incomplete in the Early Phase of the PDP, the BIW designer and cost estimator achieve insufficient results for the product cost of the vehicle body structure.

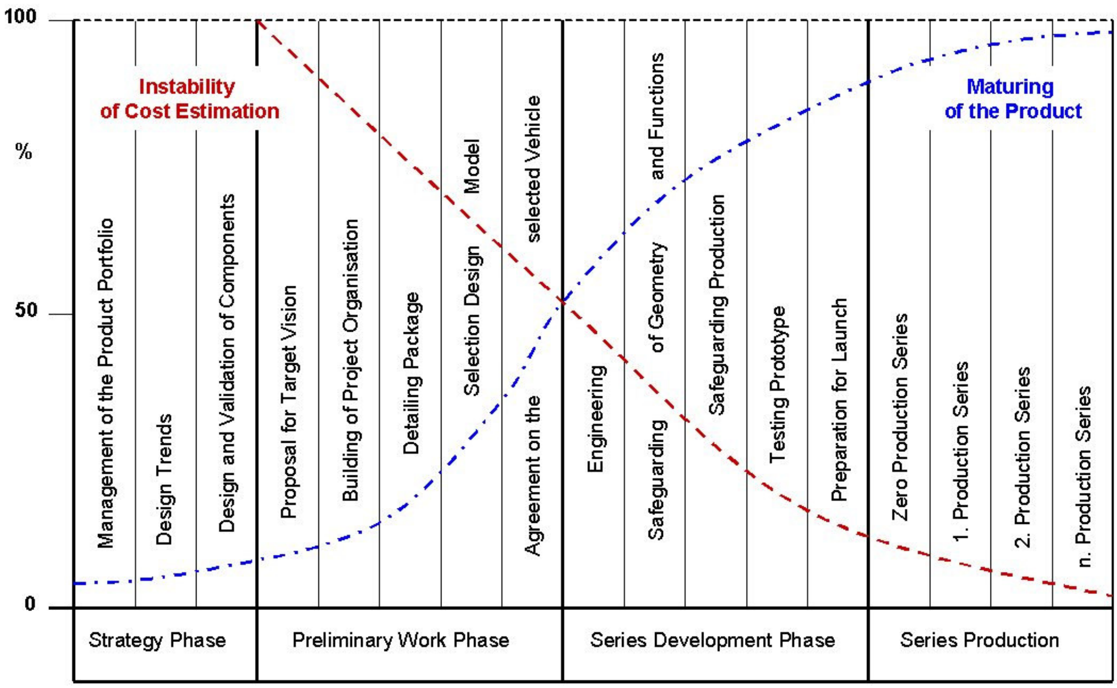


Figure 2.10: Instability of cost estimation set against the maturing of the product [Gerhard, 1994].

With reference to Figure 2.10 it could be find the acknowledgement that within the preliminary work phase the instability of the cost estimation is higher than 50% [Gerhard, 1994]. At present, estimators practise with the cost impact of many design conditions by manually adjusting the project’s activities, resources and resource productivity rates that form the basis of a cost estimate for a specific design.

Thus, cost-estimating is a typical example of a knowledge-intensive engineering task [Gahr *et al.*, 2004]. The cost estimation process is classified as a derivative task within the knowledge-based system design and optimisation process.

According to Ehrlenspiel *et al.*, [2006] Companies often hire professional estimators to perform the task. In spite of this training, designers and planners of car bodies find that there is wide variability in design cost-estimates of different estimators for the same project and that the lack of consistency in the current manual process often leads to overestimating or underestimating design costs, resulting in lost opportunities or unexpected expenses, as the case may be.

2.5.3 Classification of Methods and Applications for cost effective Designing

In the following existing methods and applications for cost effective designing will be investigated and grouped. According to Schmidt [1996], designers assume responsibility for the accruing costs of their design concepts within the company. In doing so, they can affect manufacturing cost in the preliminary phase of the PDP. In this respect, the need for early *methods and applications for cost effective designing* is ineluctable [Steffen, 1990]. In terms of positive effect on the cost objectives, the impact of design decisions has to be made transparent to the designer [Franz, 1992]. Therefore designers should systematically determine design decisions by using cost information to affect costs during the design process [Steinwachs, 1991].

Numerous methods and applications for cost effective designing are known. Therefore, only selected methods are described in detail. A more exhaustive description does not appear to be necessary at this point, because most of the methods and applications known under different names do not differ significantly from the following.

The consideration of methods and applications for cost-effective designing demands, in the first instance, a systematisation, because in the literature there is no precise classification into categories of the many and varied methods and applications. According to Gröner [1991], methods and applications for cost effective designing are separated into *qualitative methods* and *quantitative methods*, see Figure 2.11.

Qualitative methods for cost effective designing attempt to advise the designer in such a way as to steer him in a direction that will lead to a cost effective design concept. *Quantitative methods* for the design-accompanying calculation are targeted on giving the designer precise cost information that presents the costs generated from the new design concept.

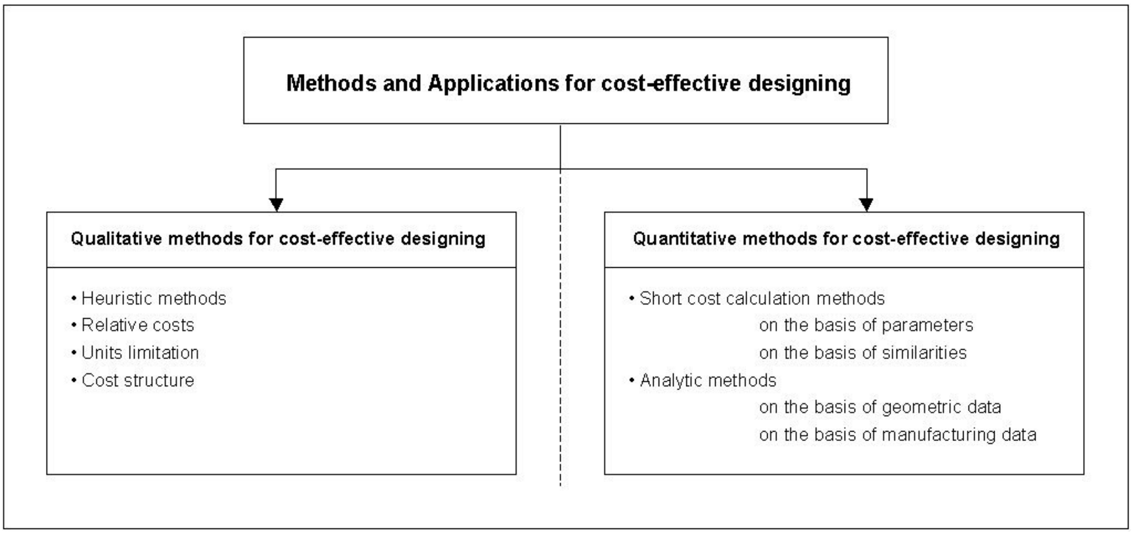


Figure 2.11: Methods and applications for cost-effective designing [Gröner, 1991].

According to Pahl and Beitz [1993], the qualitative methods for cost effective designing are generated by using cost information that presents the costs generated from past calculation of formerly-designed products. By means of the quantitative method for calculation accompanying the design, those generated provide a cost validation of the actual design concept. Schweitzer and Friedl [1993] add that therefore calculations can be based on the cost information of *accounting for actual costs* or *standard-cost accounting*. The above-mentioned qualitative methods for cost effective designing and the quantitative methods for the calculation accompanying the design are specified as follows.

2.5.3.1 Qualitative Methods for cost-effective Designing

The qualitative methods for cost effective designing can be applied even in the Early Phase of the PDP. At this stage, design concepts are not completely elaborated and only a few product-specific characteristics are established. Qualitative methods are not qualified for cost calculations because this process demands the determination of product-specific characteristics [Schaal, 1992]. Qualitative methods can merely highlight the pattern of costs resulting from alternative design concepts in order to assist the designer in finding a cost effective alternative [Gröner, 1990]. In this manner, qualitative methods support the designer in finding the cost-relevant factors or cost-effective design concepts within a concept solution. These qualitative methods are described in Table 2.1.

2.5.3.2 Quantitative Methods for cost-effective Designing

The quantitative methods, in contrast to the qualitative methods, should admit a first manufacturing cost calculation. Haasis [1994] explains that for that reason, it is called a *design accompanying calculation* method.

The intention of a design accompanying calculation is to support the designer with ascertained information about costs, which are probably caused by the new design concept. Becker and Prischmann [1994] add that with this calculation, the aim of selective designing is that the default target costs not be exceeded.

Quantitative methods can be subdivided into *short cost calculation methods* and *analytical methods*, as shown in Figure 2.11. These methods differ in their demand for data and in the accuracy of their results [Scheer *et al*., 1988].

Short cost calculation methods are characterised by means of costs established without consideration of technical details. Becker [1993] admits that for this reason, short cost calculation can provide an information basis for an economic appraisement of the design concept. Scheer *et al*. [1991] confirm that for the application of short cost calculation only a few design specific data are required. This yields a rough cost calculation with relatively uncertain solutions.

The basis of the analytical methods is the differentiated calculation procedure. By means of this procedure the design concept costs are calculated from information that belongs to the design concept solution [Ehrlenspiel *et al.*, 2006]. According to Steffen [1991], therefore, an analytical analysis of geometrical and technical details is necessary. Bock *et al*. [1990] state that this detailed information requires that the geometry and a flow chart be established. This condition is complied with at a later phase of the PDP.

Accordantly to Ehrlenspiel *et al.* [2006], it may be pointed out that analytical methods, in contrast to short cost calculation methods, require a significantly greater expenditure of data, which leads to a more precise result. On the other hand, short cost calculation methods are applicable earlier than analytical methods in the PDP. Descriptions of individual quantitative methods are given in Table 2.2.

Qualitative Methods for cost effective Designing	
Method	**Description**
1.) **Heuristic**	The heuristic methods can be characterised as a qualitative instrument that consolidates generic design experiences. Heuristic methods follow the objective of increasing the likelihood that designers will generate cost-effective design concepts [Ehrlenspiel *et al.*, 2000]. The **advantages** of heuristic methods are the industry-wide application and the long period of validation. A **criticism** of these methods is that heuristic rules do not refer to the cost structure of a product. They can affect design costs indirectly by using technical characteristics of specific product groups [Ehrlenspiel, 1985].
2.) **Relative cost**	Relative costs methods are characterised by comparing new design concept solutions to one base design concept in terms of manufacturing costs. In doing so a catalogue of appraised data is generated, which enables the designer to compare different design concepts in terms of manufacturing costs [Eberle and Heil, 1999]. The generation of relative cost results from choosing the most cost-effective or the most commonly used design concept solution with its appropriate absolute cost values as a reference object, which is allocated the value 1 or 100% [Heller and Kiewert, 1982]. In the next stage, the cost of the remaining design concept solution is compared with the cost of the reference object and tabulated by relative costs. In this way relative values are generated that are called relative costs [Deutsches Institut für Normung and Beitz, 1987]. The **advantages** of relative cost method are a function of their clarity and of the fact that they provide the opportunity of selecting early on from among the competing design concepts the one with the best promise [Pahl and Beelich, 1987]. Also, the data reliability of relative costs are in the long run more consistent. The **disadvantage** of the relative cost method stems from the extensive preparation required for gauging relative costs.
3.) **Units limitation**	Units limitation is characterised as *the number* of units in which the economic efficiency limit between two competing manufacturing techniques is achieved [VDI-Richtlinie 2235, 1987]. The units limitation method has the objective of seeking out the most cost-effective manufacturing technique if varied techniques are equally applicable [Lindemann, 1990]. It provides a cost-effective manufacturing technique for a given number of units [VDI-Richtlinie 2235, 1987]. The units limitation results from the intersection of different degressive cost-curves of product cost of competing manufacturing techniques based on the number of units. Units limitation depends on several factors, among with set-up costs, the overall size of individual parts, part-complexity, energy costs and material employed. The expressiveness of the units limitation method is comparable to that of the relative cost method [Ehrlenspiel, 1981].
4.) **Cost structure**	The method segments the costs of a reference object into its cost components [Ehrlenspiel and Pickel, 1996]. The cost structures can refer to the variable or full manufacturing costs of a product. The aim of the cost structures is to encourage the designer to handle product-related cost priorities [Pahl and Beitz, 1993]. To achieve this, dependencies between different cost categories and the product configuration are pointed out. For this reason, the cost structure method is an "important orientation guide for the approach and application of cost estimation" [Steinwachs, 1991]. In order to establish cost structures, cost analyses have to be made. As a result of these analyses, which are based on past values, similar percentage compositions can be found in the manufacturing costs of different products. Different products that show the same cost structure can be allocated to certain product groups.If a product is designed so that it is similar to a product of a certain product group, then a cost estimation can be accomplished based on the cost structure of this product group. The manufacturing cost can be approximately evaluated from a single portion of cost via equivalence-digits or direct material costs. The cost structure of a designed product is applicable during the whole design process, especially in the Early Phase of development.

Table 2.1: Qualitative methods for cost effective designing.

Quantitative Methods for cost effective Designing		
Method		Description
Short cost calculation methods	**1.) Weight cost**	Enables the designer to accomplish a cost calculation by utilising the coherences between the weight and costs of a product. The coherence between weight and costs is generated by analysis of similar design concepts. The costs are related to a unit of weight, so that a specific value can be established. An example is the manufacturing cost per kilogram of car body [Bonin, 1993]. The acquired value is applied to the product to be calculated. In case the weight of the calculated product is available, an usable method for cost-effective designing is easy to apply. Admittedly, use of the method require, that the product costs be proportional to the product weight. Furthermore, the application of the weight cost method is reasonable only for similar products [Gröner, 1991].
	2.) Material cost	Is based on the percentage coherence between material costs and manufacturing costs. This percentage coherence is converted into a parameter, like for example the percentage portion of material costs from the manufacturing cost for a product group. Therefore, the parameters are generated from the already calculated cost of past calculations of previously designed products [Becker, 1992]. For the application of the material cost method certain boundary conditions are assumed. Firstly, a constant cost structure must exist, which means that manufacturing costs preserve a consistent ratio between material costs and manufacturing costs. Secondly, variations between the new product, and the 'basis' product that was the source for the parameters have to be small. Thirdly, the ratio between material costs and manufacturing costs has to be sufficiently large; otherwise, cost calculations of labour intensive products have substantial errors.
	3.) Manufacturing cost estimation with rating equations	Relies on the assignment of costs to a product and its many technical variables [Rieg, 1992]. On the one hand, technical variables are characterised by physical functions, which are accomplished by individual parts or products. These accomplished functions are generated by physical-technical equations, so-called equations of operational demand. On the other hand, the manufacturing costs are generated by a cost equation. If the equation of operational demand and the cost equation share the same variables, at least in part, then both equations can be consolidated into a rating equation. The **advantage** of a rating equation is in revealing substantial interdependency between technical variables and their associated costs, which can lead the designer to a cost-effective design solution. A **disadvantage** of this method lies in the difficulty of generating practical rating equations. Because of the high complexity of product design, simplifications must be introduced.
	4.) Search calculation	Considers former design concepts to assist with the development of new design concepts. For this purpose, similar design products are specified in terms of manufacturability, which refers to the geometry or the manufacturing of the product design. These manufacturability characteristics are stored in an object-compilation. The specification of a product with its characteristics enables the search for similar design concepts inside of a "solution storage". The search-calculation evaluates the cost in a similar fashion by utilising the characteristic of similarity. Search-calculations are applied for preparation of "design kits" [Becker, 1993].
Analytical methods	**5.) Based on geometrical data**	This set of methods is principally applicable where geometries, metrics and tolerances are specified. These criteria are sufficiently met after the Confirmation Phase. Between geometrical characteristics of products, parts or components and their costs, functional dependencies are established. For this purpose, the costs of already manufactured products, parts or components are statistically analysed. One statistical procedure for the realisation of this process is based on regression analysis. This analysis processes the past data in such a way that a cost structure is determined and cost functions can be generated. Cost information which are generated in this way can be used in differential calculations [Becker, 1993].
	6.) Based on manufacturing data	These refer to BOM's and flow charts of existing products. This calculation scheme for products demands the elaboration and fragmentation of material bills from materials through to the finished product. Simultaneously, the manufacturing costs for each part are calculated by means of stored production steps with their flow charts. The processing time of the required production steps is multiplied with the hourly machine rate and added. Due to the fact that these calculation methods require data from the planning department, they can be utilised in the Confirmation Phase [Scheer, 1995].

Table 2.2: Quantitative methods for cost effective designing.

2.5.4 Evaluation of Methods and Applications for cost effective Designing

Initially there is an evaluation of qualitative and quantitative methods. Utilisation of these methods is assessed on the basis of the general statements that result.

The qualitative methods for cost-effective designing are applicable as early as the Preliminary Work Phase of the PDP, as indicated in Figure 2.12.

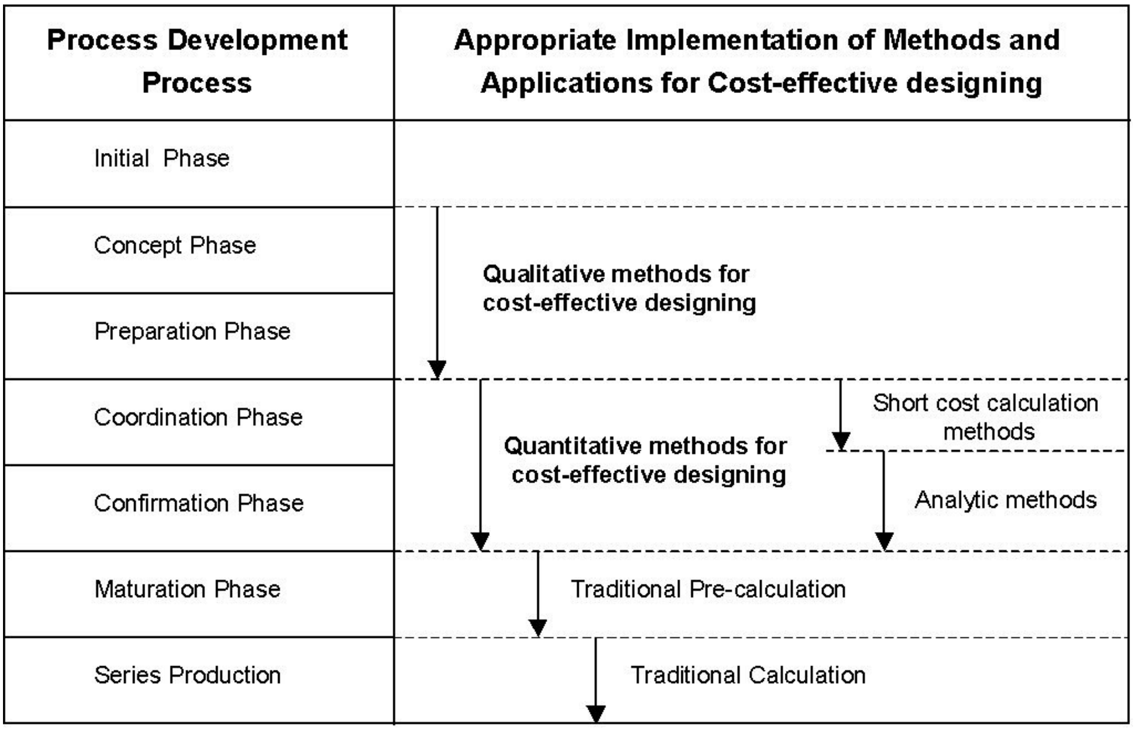


Figure 2.12: Appropriate implementation of methods for cost-effective designing in the PDP.

A disadvantage of the early applicability of these methods, however, is the fact that a proper assessment in terms of the manufacturing cost of different design concepts is difficult. This drawback can be compensated for by means of quantitative methods that have access to precise cost information.

Under the condition of the research objective to develop a cost estimation methodology that can be established in the Early Phase of the PDP and assures proper cost results for BIW design concepts, a cost-calculation of new design solutions can only be provided by a method that uses several parts of the qualitative methods. For that purpose extracts of relative-cost projection of qualitative methods can be effected to assist the designer in designing cost-effective design concepts. On the basis of concrete cost information calculations, several parts of the quantitative methods can be utilised. These available components are taken into account by the development of the BIW cost estimation methodology. A major difference between the aforementioned methods and more traditional techniques is to be found in the fact that methods and applications for cost-effective designing can be applied by the designer during the design process, as shown in Figure 2.12.

2.6 Cost Estimating methods

Because cost estimators have to make numerous assumptions and judgments about what a new product will cost [Roy and Rush, 2001], the choice of the right cost estimating method is of critical importance. Furthermore Rush and Roy [2000] state that cost estimating helps companies with decision-making, cost management, and budgeting with respect to product development.

What exactly is required of a cost-estimating method when a component or system is to be manufactured, depends on the purpose for which the estimate is to be used. According to Esawi and Ashby [2003], it may have several purposes. When the purpose is to guide competitive bidding, the method must deliver an absolute cost, and do so with precision; an error of a few % here makes the difference between profit and loss. When the purpose is to permit selection of a manufacturing process - this is our present interest - the method need only give a relative cost, which can be useful even when it is approximate: in the early stages of design or of selection an estimate accurate to within a factor of two can be helpful.

The following section provides an overview of the main methods used in the industry for cost estimating.

Parametric cost estimating

Parametric cost estimating (PCE) [Hoult and Meador, 1997] or Function-costing [Boothroyd, 1988, Allen and Swift, 1990, Wierda, 1988] interpolates the cost of a component or system as a variant of an existing family for which historic cost data are already available. This method is feasible only if two conditions are met: first, the component must be a member of a closely related family; and second, the family must have many members with established costs. These provide the historical data. Yournossi *et al.* [2002] asserts that parametric methods are based on a statistical technique that views the dependent variable (e.g., cost, development schedule) as a function of several other variables, such as size, technical characteristics, features, risk measure, etc., which are the independent variables. Accordingly to Roy *et al.* [2001], PCE is a method used to estimate the cost of future systems. Typically it is used during the early stages of development, when there is little product information available. The main principle of PCE is to develop a statistical relationship between attributes and cost of previous products in order to predict the cost of a new product. Roy and Rush [2000] state that parametric estimating can be used throughout the product life cycle. However, it is mainly used during the early stages of development and for trade studies e.g. within design-to-cost (DTC) analyses. Both industry and Government accept the techniques.

Parametric analysis has some strong advantages for estimating costs and the duration of development schedules. Its principal advantage is that after a basic parametric estimating relationship has been defined, applying the method is straightforward. Further the analyst is not to required to be a technical expert and a detailed conceptual design is not necessary to employ this method. Esawi and Ashby [2003] add that PCE has the merit that it can be applied to large, complex systems. However, it does have its limitations; for example, CERs are sometimes too simplistic to forecast cost. Inappropriately considered, a CER could provide a completely misleading result [Roy *et al.*, 2000].

Feature based costing (FBC) is a relatively new form of parametric estimating. According to Kekre [1999], choices regarding the inclusion or omission of a feature impact on the downstream cost of parts, and eventually on the life cycle costs of the product. Ou-Yang and Lin [1997]; Bronsvoort and Jansen [1994] investigate the integration of design, planning and manufacturing for cost engineering purposes using a feature based modelling approach. The FBC approach is not yet fully established, and its implications are not yet completely understood [Rush and Roy, 2000].

Similar empirical scaling

Similar empirical, or cost scaling methods can be used at the component level [Hoult and Meador, 1997, Boothroyd *et al.*, 1994, Ostwald, 1998, Weustink *et al.*, 1998, Ulrich and Eppinger, 2000, Swift, 2003]. They are based on correlations, again using historical data, for the cost of making a part with a given set of features. Thus the cost of a sheet metal part with features acquired by shearing, drawing or folding can be estimated by analysing correlations between the cost of previously made parts with these features against their size, shape and complexity, and then locating the new part in this field of costs. The method yields results of high precision; within a limited domain - such as that of sheet stampings - it is perhaps the most successful approach to cost estimation in the early phase of design process. But the requirement of correlations based on historical data for a family of closely related products made of the same materials - a narrow domain - is a very restrictive one. The approach is of little help in guiding pre-selection, for here the domain is enormous and historical data exist only for a very small part of it.

Activity-based costing

According to Cokins [1998], activity based costing (ABC) is a process for measuring the cost of the activities of an organisation. It is a quantitative technique used to measure the cost and performance of activities e.g. inspection, production processes and administration [Rush and Roy, 2000]. Each activity within an organisation is first identified and then associated with an average cost. Once this is accomplished, it becomes possible to estimate the amount of activity a product is likely to need and then associate the relative costs. Some authors [Cooper, 1988, Emblemsvag and Bras, 1994] explain that ABC seeks to calculate and sum the cost of each operational unit involved in the manufacturing of a component or system (retrieval of materials, set up time, time to perform step, de-mounting time, time to pass to next step, etc.). Information of such detail can be established only when the design is in its final phase. The method is helpful in cost cutting and for competitive bidding when established processes are in place, but it requires a formidable repository of input data – data that are not available in the early stages of design when many alternative concepts are still under consideration. Rush and Roy [2000] support this statement and claim that ABC techniques are not useful during the conceptual phase of project development.

Resource-based costing

According to Esawi and Ashby [1998], Resource-based costing assesses the resources of materials, energy, capital, time and information associated with the manufacturing of the component. The method is approximate – often values for these inputs are known only within broad limits – but it is comprehensive, equally applicable to all processes no matter how different, since all consume these basic resources. This makes the method well-suited for assessing relative cost and for guiding pre-selection. *Technical cost modelling* [Field and de Neufville, 1988, Clark *et al.*, 1997] starts from similar basis, refining it by adding more detail and incorporating sub-models for the way in which equipment and tooling cost, production rate and such like scale with the size, complexity and production volume of the component. It becomes useful when a process has been implemented and guidance is sought in optimising its operation.

Other recent developments within the cost estimating community concern the use of artificial intelligence. The implications of which are discussed below.

Neural network based cost estimation

Villarreal *et al.* [1992] claim that neural networks (NN) and fuzzy logic present the next generation in computerising the human thought processes. According to Rush and Roy [2000] for cost estimating purposes, the basic idea of using NNs is to make a computer program learn the effect of product-related attributes to cost. That is, to provide data to a computer so that it can learn which product attributes affect the final cost most. This is achieved by training the system with data from past case examples. The NN then approximates the functional relationship between the attribute values and the cost during the training.

Bode [1998] states that neural networks produce better cost predictions than conventional regression costing methods if a number of conditions are satisfied. The neural network does not eliminate any of the difficulties associated with preliminary activities when using statistical parametric methods, nor does it create any new ones. The analyst is still left with a choice of cost drivers and must commit to collecting specific cost data before analysis can begin. According to Hornik [1997], a great advantage of NN over parametric costing is its ability to detect hidden relationships among data. The NN case base must comprise similar products, and new products must be of similar nature in order for cost estimate to be effective. Thus, NN cannot cope easily with novelty or innovation. The artificial NN truly becomes a "black box" CER. This is a disadvantage if customers require a detailed list of reasons and assumptions behind the cost estimate.

A final estimating technique to discuss is the analogous method and more particularly that of case based reasoning.

Case based reasoning

Rush and Roy [2000] state that analogy makes use of the similarity of products. The implicit assumption is that similar products have similar costs. By comparing products and adjusting for differences it is possible to achieve a valid and useable estimate. The method requires identifying both the similarities and differences of items. This can be effected on the basis of experience or through databases of historical products. Case-Based Reasoning (CBR) can also be classed as a form of artificial intelligence since it can be used to model, store, and re-use historical data, and capture knowledge for problem solving tasks. An important feature of CBR is the ability to learn from past cases. A CBR system stores and organises past situations, then chooses a situation similar to the problem at hand and adapts a solution based on the previous cases.

The previous section has shown several state-of-the-art-techniques used to effect cost estimating, particular emphasis being given to their applicability. This provides a broad overview of the strengths and weaknesses of each method. It is apparent that activity based costing, resource based costing and neural networks cannot be used during the earlier product phases in the PDP, a result in complete accordance with the assumptions of the research aim. Furthermore neural networks cannot easily cope with innovative developments, which in the case of BIW design are central. Parametric cost estimating methods are sometimes too simplistic to forecast cost and could provide a completely misleading result. An empirical scaling method based on historical data for a family of closely related products made of the same materials is a domain too narrow and restrictive to be applicable to BIW cost estimating. The case based reasoning method, which presupposes the similarity of products, is also not appropriate for BIW cost estimating.

The consideration of state-of-the-art- cost estimating techniques shows, therefore, that there is no ‘off-the-shelf’ solution available for the BIW cost estimating problem.

2.7 Discussion of the Literature Review Findings

The shortening of the total development time, hence of the Preliminary Work Phase of the PDP, automatically narrows the time-range of cost estimation and calculation. This led to the need of a cost estimation methodology tailored to the requirements of design in the Early Phase of development process. Furthermore there is a strong effort to achieve a reduction of car body weight by the application of light-weight materials, which require new Joining Technologies. These technical changes are making cost estimates more difficult, while increasing manufacturing costs are making them more necessary. It became obvious that the use of BIW Working Contents will be fundamental to the cost estimating process.

2.7.1 The Need for a Cost Estimation Methodology

After an initial review of the subject areas listed in the introduction to this chapter, it became apparent that the literature currently available offers no obvious ‘off-the-shelf’ solution to the cost estimation problem of BIW design in the preliminary phase of the PDP. The approaches described indicated partial solutions, and useful tools and techniques for their implementation, but none of these provides a holistic approach to the problem.

This led the researcher to the view that there is a gap in the literature as well as in industrial practice when it comes to the design and implementation of cost estimating processes for BIW design in the Early Phase of the PDP.

There is a constantly growing demand for greater effectiveness and higher efficiency in the design and manufacturing engineering processes of the automotive industry. The new product strategies of a car manufacturer involve the overall business driver: to shorten the design processes, to improve fuel consumption by reducing car body weight, and to get greater control over product cost by improving early cost estimation. At present this latter is a lengthy procedure that can take up to several months and requires input from three different departments, as shown in section 2.4. Automotive practice requires new methods and processes to enable the designer to determine the future manufacturing costs of new BIW design concepts in a short period of time. In view of currently known and utilised methods and applications of cost-effective design - as indicated in section 2.5.3 - it is clear that these methods and applications are not directly transferable to the new requirement for rapid product development. The intended research work will use these methods as a basis for further development of a cost estimation methodology.

Given that somewhere between 60% and 85% of manufacturing costs are established during the Preliminary Work Phase by the design department, it is essential to provide BIW engineering with a rapid cost estimation process.

All these considerations emphasise the need for the development of a methodology capable of providing a systematic approach to the comparison of future manufacturing costs of BIW design concepts, and thus of assisting with cost reduction in the Early Phase of the PDP.

2.7.2 Novelty of the proposal for a Cost Estimation Methodology

The literature review of the BIW design process and the active integration of the design, planning and finance departments has shown that a structuring of the work sequence and of WC's is of critical importance for the development of a cost estimation procedure. The idea behind the proposed approach is to represent the design concept using WC's, which are further expressed in JT's. WC's in this situation can serve as a common denominator to the departments mentioned in section 2.4.3. A designer has to make a decision as to the most effective combination of JT's for his design concept with regard to manufacturing cost. Cost estimating and reduction by supporting the joining process selection represents a new approach in the area of cost estimation in the Early Phase of the PDP. The suggested approach provides the design department at the end of the design process with a comparison of relative manufacturing costs of different new BIW design options in the Preliminary Work Phase of design. This methodology is primarily intended to be used by the design department and, in contrast with former processes, is not restricted to the planning and finance departments alone.

2.8 Summary

The literature review verifies the assumption that no existing process provides the Body-in-White designer with a systematic approach to the comparison of relative manufacturing costs of different new design concepts in the Early Phase of development. The review stresses the impact of cost management on the product development process, as well as the difficulties and challenges faced by companies that compete in today's market and have come to realize that new cost estimation systems are a requirement of critical importance. A further discussion of the tasks and main phases of a generic vehicle Product Development Process has been introduced to reveal coherences in the development sequences systematically. Hence the integrated process of Body-in-White design has been presented with its high requirements to the car body designer. In this context the customer demand for improved fuel-efficiency by reductions in car body weight became apparent. Hence the application of light-weight materials requiring the use of new Joining Technologies must be taken into account. In this context the proportion of Body-in-White to total car cost - the overall business driver of the research project - is established.

On the basis of a current example of a car body the relevance of Working Contents within the Body-in-White design process and the cost estimating process has been shown. It became apparent that Joining Techniques are the main cost driver in the Body-in-White manufacturing process. Therefore an outline is given of the various Joining Techniques currently used in car manufacturing.

Another step for the development of a cost estimation methodology is the analysis of interactions between Design, Planning and Finance with its current time consuming cycle of information exchange. In the present state of affairs the Body-in-White designer simply does not get enough information to permit an early cost estimate of his design concepts. To meet this need a chart showing the various domains of knowledge characterising each of the aforementioned departments has been developed to shorten the time of information exchange.

Subsequently there is a classification of methods and applications for cost-effective designing on the basis of whether they are qualitative or quantitative. Thereby it becomes apparent that no off-the-shelf cost-effective designing methods are directly applicable to the cost estimation of new Body-in-White design concepts. Only components of these existent methods are used for the development of the Body-in-White cost estimation methodology proposed. Additionally main methods used in the industry for cost estimating were introduced and scrutinised for applicability to the research problem.

The subsequent discussion of the literature review findings deals with the need of a research methodology that can shorten the design and cost estimating procedure for the Early Phase of the development process. Finally, the novel approach of cost estimating that consists in using Working Contents to expedite selection of the most cost effective combination of Joining Techniques for a new Body-in-White design is introduced.

3 Research Methodology

3.1 Introduction

The description and development of the original problem in the previous two chapters led to the research project and the literature review, which produced a series of arguments showing the need for a cost estimating tool in the Early Phase of product development. This in turn led to development of the research hypothesis, for the testing of which a research methodology had to be fixed upon. This methodology will be considered and defined in the present chapter.

A critical issue for any researcher is how to explore, describe and explain the problem treated [Blaikie, 1991]. Chapter 3 opens with a general definition of what research methodologies are available and which are appropriate to the present research. The research paradigm provides the framework for the study by specifying 'what we can know', 'how we can know it' and 'what role the researcher plays'. The research strategy will be outlined, including decisions as to which type of data to collect, which research design to use, and how the role of the researcher should be construed. The research strategy determines the choice of data collection methods, as well as the approach to the process of data analysis. The procedures followed are outlined in detail.

3.2 Definition of the Research Methodology

A research methodology is a set of principles that may be reduced to a method uniquely suited to a given situation. A methodology is a body of methods, procedures, working concepts, rules and postulates employed in science, art or some other discipline. It is a process of inquiry, rather than a method that produces a predetermined result. It also enables the investigator to develop a plan for studying a situation, permits iterations between research stages and defines the investigator's role [Blaxter *et al.*, 1996]. In addition, it makes it possible for the objectives of the study to be stated, reviewed and modified [Bignell, 1991].

It is widely accepted that the research approach, design and methods should be chosen on the basis of the research objectives to be achieved [Easterby-Smith *et al.*, 2001; Saunders *et al.*, 2002]. One of the general principles of a Research Methodology is that there is usually no one best approach but rather that the approach most effective for the resolution of a given problem depends on a large number of variables, of which the nature of the problem itself is not the least.

According to Gill and Johnson [1997], a research methodology is always a compromise between options, and choices are frequently determined by the availability of resources. It is helpful conceptually to separate the content of the task from the way the task is accomplished; that is, to separate the content (what) from the process (how). [Schutt, 1996] adds that research methods based on this analysis are then primarily concerned with how (process) to tackle tasks (content). It should be borne in mind that "the research process is not a clear-cut sequence of procedures following a neat pattern, but a messy interaction between the conceptual and empirical world, deduction and induction occurring at the same time" [Bechhofer *et al*., 1984].

3.3 Research Methodologies

The purpose of this chapter is to

a) define and justify the methodology of the research.
b) present and discuss the inquiry method selected to collect data.
c) describe the process of data analysis and treatment.
d) reduce different types of bias by using the right data collecting technique.
e) present a method for evaluating the research.
f) discuss the methodology of the case studies.

Research methodologies are generally classified into two basic groups; namely, the quantitative (or scientific) and the qualitative (or interpretative) [Robson, 1995]. The former approach is also sometimes referred to as the "traditional approach" and is commonly associated with laboratory experiments, mathematical modelling, etc.

Checkland [1994] designates these two approaches as "hard systems" and "soft systems" thinking, respectively. In addition, the former is usually related to the scientist and the second to the engineer or technologist.

To understand the purpose of each, Checkland [1978] provides the following example: where the scientist asks: "have we learnt anything?", the engineer asks: "does it work?".

According to Avision [1999], qualitative research (e.g. case study, grounded theory, etc.) is now accepted as equal in value to quantitative research (e.g. mathematical modelling, statistical analysis, etc.) when used appropriately. The following section presents both research methodologies with a discussion of their main strengths and weaknesses. It states which was found more suitable for the research. However, it should be borne in mind that there is no perfect methodology [Garson, 2002].

3.3.1 The quantitative Methodology

The purpose of scientific or quantitative methodologies is to establish proven knowledge about the world and our place in it. According to Checkland [1978], its method, the carrying out of reductionist, repeatable experiments, which aim to test hypotheses, has been attended by notable success.

Quantitative approaches are built upon a foundation of premises and beliefs, including the assumption that data must yield proof or strong confirmation of a theory or hypothesis in a research setting. Robson [2002] states that the purpose of the quantitative approach is to develop causal laws, where data are derived from the use of strict rules and procedures fundamentally different from common sense.

Strengths: According to Burns [2000], the quantitative approach has a number of strengths. First, it has control and precision that is achieved through sampling and the design of experiments and through reliable quantitative measurements. Second, the value of a variable can be shown to have a direct causal effect on another when other variables have been controlled. Third, hypotheses are tested through deduction with the use of quantitative data permitting statistical analysis.

Weakness: The scientific approach is not the most suitable to apply in real world situations because its objectivity does not allow the subjectivity of the social action of reality to be taken into account [Robson, 2002]. Based on the assumption that facts are objective and the same for all people at all times, it fails to take account of people's unique ability to interpret their experiences, construct their own meanings and act on these [Burns, 2000]. In addition, Robson [2002] states that quantitative research restricts experience in two ways: first by directing research to what is perceived by the senses; second by employing only standardised tools based on quantifiable data to test hypotheses.

Furthermore, Burns [2000] argues that there is a lack of flexibility with this approach because the criteria considered appropriate for the research are not necessarily appropriate for the work that rests on different assumptions, uses different methods and appeals to different forms of understanding.

3.3.2 The qualitative Methodology

Within a qualitative methodology, the world is seen as problematic and such that it should be studied systematically. According to Checkland [1988], this methodology is a systems-thinking approach to "messy" real-world problem situations dominated by different attributes of meaning. Gerson and Horowitz [2002] suggest that this methodology is concerned not only with objectively measurable "facts" or "events", but also with the way in which people construct, interpret and give meanings to the experiments.

Moreover, it offers ways of examining the intervention itself, as well as the problem situation, as both a social system and a political system [Checkland, 1994].

Furthermore, according to Mingers [1984], qualitative research is action-oriented, its purpose being to facilitate taking action in the real world in order to bring about change.

Strengths: The main advantage of the interpretative methodology is that contact with participants is possible at various levels in a manner more likely to provide accounts of events with depth as well as breadth [Bryman, 2001]. Eisner [1979] describes this approach as being highly relevant because it is concerned with processes rather than consequences, wholeness rather than independent variables, and meanings rather than behavioural statistics.

Also Flick supported this statement; Flick argues that researchers are increasingly confronting new contexts and perspectives [Flick, 2002]. Avison [1999] pointed out that a particular strength of qualitative methods is their value in explaining what goes on in organisations.

Weaknesses: A limitation of qualitative approaches is the difficulty of applying the standards of reliability and validity needed for evaluation [Shaw, 1999]. Parlett argues that intimacy between participant and observer affects the result. On the other hand, the observer needs to gain some confidence with the participant in order to retrieve quality information [Parlett, 1976]. In addition, the promise of anonymity, which often serves as the basis for trust, together with the requirements for authenticity, makes the task of the researcher difficult. Another weakness of this approach is that the researcher needs to spend a considerable amount of time in the research setting in order to examine the interactions, reactions and activities of subjects.

3.3.3 Types of Research Methodologies

According to Jenkins [1991], the following methodologies are pertinent to research work.

- Quasi Experiments
- Laboratory Experiments
- Action Research
- Survey Research
- Case Study Research

Consideration of the present area of research shows that survey and case study research are the most appropriate methodologies for pursuit of the research work. Consequently a survey is conducted in the initial stages of the research and a case study is carried out for validation of the optimisation methodology developed. In the following both these types are described in detail.

3.3.3.1 Survey Research

Survey research is the method of collecting information by asking a set of pre-formulated questions in a predetermined sequence in the form of a structured questionnaire to a sample of individuals drawn so as to be representative of a defined population [Hutton, 1990]. Thomas [1996] describes a survey as a procedure in which information is collected systematically about a set of cases (such as people, organisations, objects). Thomas goes on to argue that surveys resemble laboratory experiments; they are sometimes used purely for data gathering or they are used to test hypotheses or to estimate relationships between variables. Gill and Johnson [1991] share this point of view. They say that survey research can be applied in two different ways, depending on the researchers' objectives. It can be used to test existing theories and, in such a case, to transfer the principles of the true experiment into a real setting.

Key issues in this explanatory or analytical survey are sample size, data collection procedures, analysis and measurement.

The aim of the alternative approach is to explore an area in order to identify existing correlations. In such a survey, open and probing questions will be asked. In a transition from questions like "how many" to "why", no doubt, analytical surveys are the ones indicated. Collecting information by means of survey research has a number of distinct advantages over alternative methods of collecting similar information. According to Hutton [1990], these are the following:

- *Questions are designed so that answers from individual interviews can be added together to produce results, which apply to the whole sample*. This is further facilitated by the fact that questions are asked in a systematic way.
- *The research is based on interviews with a representative sample of respondents* as far as is practical. This means that results from the survey can be projected onto the population as a whole, with a calculable degree of reliability.
- *The questions are designed to be unbiased* in the sense that they are phrased in such a way that no preferred answer is implied.
- *Surveys lend themselves to future replication* because the questions, the interviewing technique and sampling are tightly controlled. Thus a survey can be repeated one, two, three or more months or years or decades later to assess the degree of change in the intervening period.

Czaja and Blair [1996] subdivide survey research into five stages:

Stage 1:	Survey Design and Preliminary Planning
Stage 2:	Pre-testing
Stage 3:	Final Survey Design and Planning
Stage 4:	Data Collection
Stage 5:	Data Coding, Data-File Construction and Analysis

Within each stage there are a number of activities to be undertaken and decisions to be made. Czaja and Blair also point out the potential need for iterations within and between stages. This means, for example, that, even with careful planning in stage 1, there will be changes in the following stages due to the outcomes of the testing or the monitoring of the actual data collection.

3.3.3.2 Case Study Research

Case study design is "a specific way of collecting, organising and analysing data. According to Patton [1990], the purpose is to gather comprehensive, systematic and in-depth-information about each case of interest".

Case study research is but one of several ways of doing social science research. Yin [1994] states that it is generally the preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events and when the focus is on a contemporary phenomenon within some real-life context. Yin calls these "explanatory" case studies and points out that there are other forms, namely "exploratory" and "descriptive" case studies. This statement is also supported by Robson [1993].

Exploratory research is undertaken so that new insights may be gained into poorly understood phenomena [Zikmund, 2000; Solomon, 1996]. The central idea is to identify new problems and generate hypotheses to be tested in future research [Welman and Kruger, 2001; Marshall and Rossman, 1999]. According to Kjellen and Soderman [1980] case study research is a useful strategy for studying processes in companies and also for explanatory purposes.

An important advantage with case study research is the opportunity for a holistic view of a process [Valdelin, 1974].

Holism may be viewed as the opposite of reductionism [Capra, 1982]. Case studies can be of particular value in the applied sciences, where research often aims to provide practitioners with tools [Alloway, 1977].

A frequent criticism is that case study research is inferior to methods that are based on random statistical samples of a large number of observations. Bonoma [1985] argues that during recent years, case study research has received growing recognition among groups of management researchers in Europe.

A number of researchers propound the careful examination of a few cases rather than trying to generalise over hundreds of cases [Kirk and Miller, 1986; Gill and Johnson, 1991; Gummesson, 1999; Stake, 2000], and consider quality and depth more important than mere sample size.

Summarised below are general points of criticism towards the case study research methodology. One argument brought against case studies research is that case studies are often sloppy investigations where equivocal evidence or biased views influence the direction of findings and conclusions. Important arguments against this statement are given by Yin [1994], who states that bias can reduce the quality of any research and that a case study carried out by following a stringent methodology can be of high quality and reliable. An additional argument against the case study is that of reduced generalisability. Another weakness of the case study method concerns its presentation; namely, that it is too long and cannot be readily analysed. This line of argument is countered by Yin [1994], who says that it is a question of the presentation format and its structure, and that cases can be described in an acceptable length. The methods for carrying out case study research presented in Robson [1993] and Yin [1994] have in common that a theoretical or conceptual framework has to be used or developed before the case study can be developed. The aim of such a framework is to guide data collection and analysis [Popper, 1996].

It is important to note that following the drawing of cross-case conclusions, the theory on the basis of which a case study was designed may have to be adjusted as a result of the findings of the study [Popper, 1994].

3.3.4 Evaluation and Selection of the Research Methodology

Qualitative methodologies do not have the intention of creating rigorous models of the system, despite the role played by empirical observation [Jones, 1978]. Thus, Jackson [1982] argues that quantitative methods should not be used in studying either the social world or information systems because their complexities are best addressed by methods of the social sciences. The qualitative and quantitative approaches are now of equal value for research. McKie [2002] argues in addition that qualitative research is appropriate where potential outcomes are not clear in advance. Moreover, despite much Management Information System (MIS) research following the traditional conventions of scientific methods [Tranfield, 1983], the qualitative approach has been applied successfully to Information System (IS) development [Symons and Walsham, 1989].

This methodology has also been successfully applied by Ince [2000] and Silva [2002] when developing a methodology for capturing user requirements for Information System design and optimisation. In view of the strengths and weaknesses of each methodology, and of the valuation of the above mentioned arguments, the qualitative approach seems to be to be the most suitable for carrying out the present research work because the initial problem is not of a statistical nature making the quantity of data essential. This research problem is associated with singular technical processes where the contact with participants at various levels is of critical importance.

As will be seen later, some data collection and analysis methods traditionally used within quantitative approaches are also used.

Even though Garson [2002] states that there is no perfect methodology for conducting research, the qualitative methodology has been found most appropriate for the present study. In addition, the research will have an exploratory purpose, which is a feature of qualitative research. As to the research strategies, they are usually resolved into five distinct strategies: experiments, surveys, archival analyses, histories and case studies, and surveys [Yin, 1994].

An industrial survey, based on questionnaires, interviews and analysis of documents has been used in this research to give a detailed insight into the design, planning, finance and manufacturing activities of BIW development, although an industrial case study has also been conducted to validate the new developed optimisation methodology of this research work. The following sections present the data collection, analysis and evolution strategy that has been followed according to the research approach adopted.

3.4 Data collection Methods

Although many have the impression that data collection is the major enterprise in research, this is not strictly correct. Preparation takes the most time, and drawing conclusions and writing the report takes more time than data collection in most cases. Babbie [1990] adds that the evidence collected by the research process is called data. Data are facts produced by research. Data are not abstract; they are concrete, they are measurements of the tangible, countable, sensate features of the world. Data are usually called quantitative if they are in numerical form and qualitative if they are not. Pursuant to Trochim [2000], proponents of each type of data often argue the superiority of their kind of data over the other. Those in favour of the quantitative types argue that their data is hard, rigorous, credible and scientific, whereas proponents of the qualitative types counter that their data is sensitive, nuanced, detailed and contextual.

In our research work both data types will be relevant. Getting data from the Design, Planning and Finance means getting mostly quantitative data. Data from the manufacturing area will be mostly of the qualitative type.

The following section will assess the "from where and from whom we are going to get the information", and "how we will get the information".

3.4.1 Data collection Techniques

This section introduces a range of data collection techniques. Each technique is described briefly, along with its strengths and weaknesses. It discusses data collection techniques that could be used to gather information in a real world context.

3.4.1.1 Interviewing

As in many forms of qualitative research, interview data are usually favoured as a means of illustrating findings and supporting the developed theory [Bloch, 1996]. Interviewing is a data-collection technique relied on quite extensively by qualitative researchers. It is often described as "a conversation with a purpose" [Miller *et al.*, 1997]. Interviewing as a research method typically consists of a conversation [Kvale, 1996] for a specific purpose, in which the researcher asks questions and the respondent answers them [Rubin and Rubin, 1995].

An interview is a method of data collection that may be described as an interaction involving the interviewer and the interviewee the purpose of which is to obtain valid and reliable information [Golden, 1997]. Interviews may range from casual conversation or brief questioning to more formal, lengthy interactions [Gummesson, 1993]. The interview is the main road to multiple realities [Dexler, 1970]. Interviews have particular strengths and weaknesses [Mantwill *et al.*, 1995]:

Strengths: An interview is a useful way to get large amounts of data quickly. When more than one person is used as an informant, the interview process allows for a wide variety of information and a large number of subjects. It also allows for immediate follow-up questions and, if necessary, for clarification.

Weaknesses: Interviews must involve personal interaction; cooperation is essential. Interviewees may not be willing to share all the information the interviewer needs. The interviewer may fail to ask appropriate questions because the interviewer lacks expertise or familiarity with technical jargon; conversely the interviewer may fail to comprehend properly the answer given.

The research methods literature [Patton, 2002; Yin, 1994] suggests that interviews are an appropriate means for exploring what is in an automotive developer's mind and for getting at data that cannot be directly observed.

Interviews may take many forms: they may be structured, unstructured, group, face-to-face or conducted over the telephone. With grounded theory the most common form of interview is the face-to-face unstructured or, more realistically, semi-structured, open-ended, ethnographic, in-depth conversational interview [Goulding, 2002]. It should also be flexible enough to allow the discussion to lead into areas which may not have been considered prior to the interview but which may be potentially relevant to the study [Fontana and Frey, 1994].

According to Robson [2002], in circumstances where individual perceptions of a process within a social unit, such as a work-group, department or whole company, are to be studied prospectively, qualitative research interviews are the most appropriate. In addition, Wengraf [2001] argues that interviews are designed for the purpose of improving knowledge and for going into matters in depth.

Semi-structured interviews: have pre-determined questions, although the order can be modified based upon the interviewer's perception of what seems more appropriate [Bechhofer *et al*., 1999; McCrone *et al*., 1998]. Finally, in the unstructured interviews there is no standardised list of questions. The interview takes the form of a free-flowing conversation between interviewee and researcher.

Short ad-hoc interviews: are useful for "quick problem solving". To fill in small gaps in data collections, a short ad-hoc interview, whether by telephone or face-to-face, is undoubtedly best. In cases where internal documents have to be analysed, difficulties in understanding are frequent and are best remedied by a short ad-hoc interview.

A topic guide [Easterby-Smith *et al*., 1991; Patton, 1987] was used to provide the necessary structure and to ensure that key areas of interest would be explored,Table 3.1.

- To what extent is your department in a position to estimate manufacturing cost in the Early Phase of Development?
- What kind of data are available in your department for the estimation process?
- What source of data would be of help to you in working out an estimation?
- How long does it take to obtain information from the data source?
- In which phase of the development process you can start with the estimation?
- What are the main obstacles for cost estimation in your department?
- Would you expect a new cost estimation tool to have an impact on your decision making?

Table 3.1: Example of topic guide for Design, Planning, Finance and Manufacturing.

The topic guide was updated on the basis of what emerged from the analysis of previous data. The number of interviewees and the time of interview are difficult to specify because they depend on the organisation's availability and the informant's agenda. As a next step, the interview process also involved a questionnaire that informants were asked to complete once the interview was concluded. The combination of interview and questionnaire has been used by Hansen *et al.* [1980], Ince [2000] and Oskamp [1977] for collecting qualitative data.

3.4.1.2 Questionnaires

If interviews are, as was argued in the previous section, unavoidably fluid because they are a species of social interaction, structured questionnaires are a means of trying to control that uncertainty [Heath *et al*., 1994]. Structured written questionnaires can be administered either by interview or by post [Oppenheim, 1992], although these two types of data collection involve somewhat different question formats [Hart, 1998]. For postal survey they are, in fact, the only realistic option. In other words, there are clear instructions with relatively simple questions and relatively straightforward ways of answering them. One cannot really expect people to write essays in reply to postal questionnaires [Cannell *et al*., 1981]. In using questionnaires, researchers rely totally on the honesty and accuracy of the participants' responses [Marshall and Rossman, 1989].

Questionnaires typically entail several questions that are open-ended or have structured response categories [Munn and Drever 1990].

3.4.1.3 Analysis of internal Documents

The analysis of documents and other kinds of text in already published or otherwise available form can be immensely rewarding; there is an excellent discussion of this type of research in Scott [1990]. Within each company, the documentation and information about different kinds of technical processes are extensive. The aim of the analysis of internal company documents is the extraction of important data. Difficulties in extracting proper data out of the "data flood" could by solved via ad-hoc interviews or ad-hoc meetings with experts who are responsible for the internal data source. These kinds of data were of critical importance to our research for the development and validation of the cost estimation process.

3.5 The Research Strategy

The exclusive use of qualitative data collection techniques is not a requirement. According to Stake [1995], the strategy is a road map, an overall plan for stimulation interest in systematic inquiry. A case study can use several techniques to elicit the desired information. Some techniques are usually associated with specific strategies, but rather than dictate whether qualitative or quantitative data will be gathered, the overall approach frames the study by placing boundaries around it and identifying the level of analytic interest. Marshall and Rossman [1989] point out that the research strategy reflects a series of major decisions made by the researcher in an attempt to ascertain the best approach to the research questions in the conceptual portion of the proposal.

A research process having been defined and a number of research methodologies and pertinent evaluation criteria having been described, it remains to consider the development of the overall research strategy. According to Bennett [1991], Gill and Johnson [1991], Popper [1994] and Blaxter *et al.* [1996], the following three factors must go into the formulation of the research strategy: (i) the research question / problem (ii) the research setting and political context (iii) the resources available.

A definition of the overall research strategy must involve a) consideration of these points, b) bringing together the methodologies that deliver the maximum overall validity, and c) integrating these methodologies into the research process.

In the previous section the theory of the research process and the available methodologies were described, and the validity of the various research methodologies was discussed. This section sets out to define the chosen research process and the methodologies applied within it.

3.5.1 The Environment of the Research Strategy

In the following section the various ways in which the circumstances surrounding the research had an impact on it are listed and discussed.

3.5.1.1 The Research Hypothesis

The design department commissioned the research because they realised that at present there is no readily available methodology that can provide the BIW engineering department with a systematic approach to the problem of how to compare the costs of different new design concepts in the Early Phase of the development process.

The previous literature review provided evidence and the following hypothesis:

"It is possible to develop a methodology for estimating the relative manufacturing costs of different BIW design concepts using the information contained in the design specification data of the new design concepts."

This statement is of critical importance for the development of the cost estimation methodology.

3.5.1.2 The Research Setting

The content of the research problem was motivated by the development of a new car. The decision to substitute aluminium for steel in the front-end, made in the course of the series development phase, overtaxed the capabilities of the regular cost estimation process. Thus was born the demand for a new and quick cost estimation process within the BIW engineering department. As the PDP will, in future, be shortened, a linking together of Design, Planning and Finance will prove inevitable.

The project received support from the BMW R&D Centre. Design, Planning, Finance and Manufacturing were the main sources from which data were to be gathered. These departments were intimately involved with the research process, so it was clear from the start that the outcome of the research work would not only be a theoretical methodology, but also a practical, applicable process. Overall, the researcher had the opportunity to view the performance of the process from a number of angles. This will be reflected in the actual set-up of the research work.

3.5.2 Research Methodologies adopted

A number of different research methodologies improve the overall validity of the research. Table 3.2 provides the researcher with a framework for deciding on the most adequate and efficient research strategy. While Yin [1994] would assert that a strategy does not, ipso facto, determine particular data collection techniques, Marshall and Rossman [1989] have found that, in practice, qualitative techniques go quite naturally with certain overall strategies.

In light of earlier studies on research methodology (see section 3.3.3), the goal of the present study (cf. Table 3.2), which is (i) to identify or discover important variables and (ii) to generate hypotheses for further research, seemed to make clear that the research would best be carried out by means of exploratory case studies. In addition, a survey was made, for which the reasons are given below.

3.5.2.1 Survey Research - Justification

In the initial stages of the research, a survey was conducted with a fourfold purpose: (i) to justify the research, (ii) to focus the research, (iii) to define the problem, and (iv) to outline a strategy for solving the problem. The following objectives were defined to:

- Identify any gaps in the literature.
- Identify the strengths and weaknesses of current cost estimation systems.
- Identify relevant findings to justify the research.
- Identify information pertinent to the problem.
- Identify optimisation processes necessary for the cost estimation methodology.

Purpose of the study	Research Question	Research Strategy	Examples of Data Collection Techniques
EXPLORATORY 1.) To investigate little understood phenomena 2.) To identify / discover important variables 3.) To generate hypotheses for further research	a.) What is happening in this social program? b.) What are the salient themes, patterns, categories in participants' meaning structures? c.) How are these patterns linked with one another?	a.) Case study b.) Survey c.) Field study	a.) Participant observation b.) In-depth interviewing c.) Elite interviewing
EXPLANATORY 1.) To explain the forces causing the phenomenon in question 2.) To identify plausible causal networks shaping the phenomenon	a.) What events, beliefs, attitudes, policies are shaping this phenomenon? b.) How do these forces interact to result in the phenomenon?	a.) Multisite case study b.) Life history c.) Field study d.) Ethnography	a.) Participant observation b.) In-depth interviewing c.) Survey questionnaire d.) document analysis
DESCRIPTIVE 1.) To document the phenomenon of interest	a.) What are the salient behaviours, events, beliefs, attitudes, structures, processes occurring in this phenomenon?	a.) Case study b.) Field study c.) Ethnography	a.) Participant observation b.) In-depth interviewing c.) Survey questionnaire d.) document analysis e.) unobtrusive measures
PREDICTIVE 1.) To predict the outcomes of the phenomenon 2.) To forecast the events and behaviours resulting from the phenomenon	a.) What will occur as a result of this phenomenon? b.) Who will be affected? c.) In what ways?	a.) Experiment b.) Quasi-Experiment	a.) Survey questionnaire (large sample) b.) Kinesics / proxemics c.) Content analysis

Table 3.2: Matching Research Questions with Strategy [Marshall and Rossman, 1999].

In the course of the industrial survey, data capable of helping in the attainment of the above listed objectives and of enhancing the argumentation were gathered from a variety of sources. Questionnaires, interviews and analysis of internal documents were the main techniques used for gathering data. The descriptive framework presented in Figure 3.1 summaries the methodology followed in the inquiry process.

3.5.2.2 Case Study - Justification

The present section is devoted to the methodological sequence followed in an industrial case study. The goal of the latter was to evaluate the developed methodology of optimal Joining Technology selection that makes it possible to estimate the relative manufacturing cost of different BIW design concepts, and further, to justify the practicability and the benefit of this overall methodology. The following objectives were set down.

- Calculate the relative manufacturing cost of a real world BIW design concept by using newly developed methodology.
- Verify the results of the calculation.
- Identify further advantages and disadvantages of the Joining Technique selection methodology.
- Specify the field of application whereby the user of the methodology can identify cases in which the user can obtain suitable results.
- Validate the new optimisation methodology.

These objectives were to be reached by means of a case study designed for that purpose. The new developed methodology will be tested in the BIW engineering department, which, in future, will be the main user group of the new estimation methodology.
Therefore interviews are also conducted with experts from Design, Planning and Finance for gathering data from the real world BIW design concept example.
Subsequently a questionnaire will check the applicability of the new methodology. Finally the boundaries and opportunities of the new optimisation methodology will be shown in the case study.

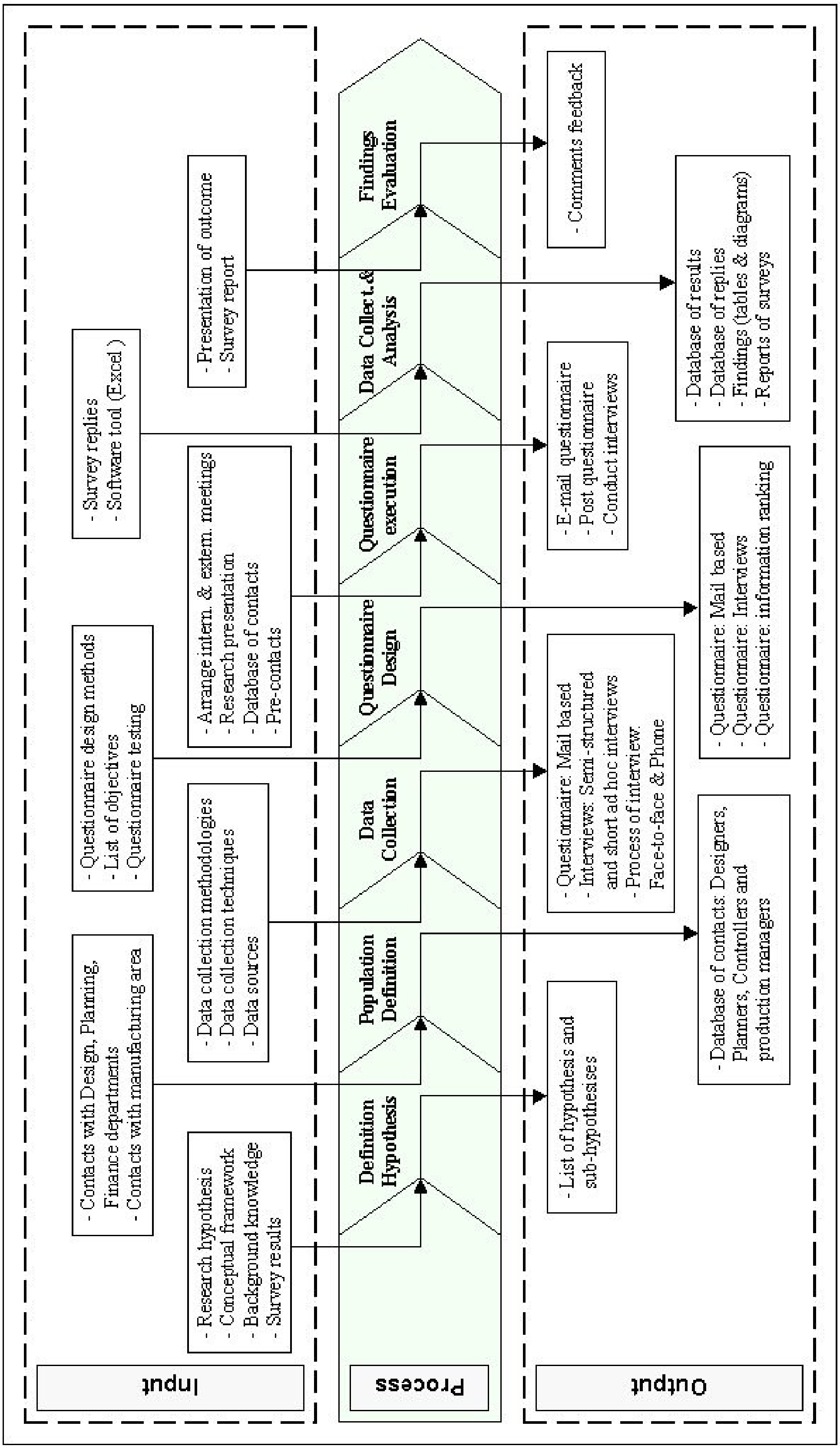


Figure 3.1: Survey research sequences.

3.5.3 Data Collection Techniques adopted

In any production plant, there are four different groups of participants, each of which has its own perspective. On one hand, there are Design, Planning and Finance, which cooperate closely in the Research & Development Centre; on the other there is the manufacturing area.

Semi -structured Interviews	❖ Explore the understanding and acceptance of the need for a new cost estimation tool. ❖ Identify the strengths and weaknesses of actual cost estimation tools. ❖ Explore perceptions of the helpfulness of the new cost estimation tool.
Short ad-hoc Interviews	❖ Get a first understanding of problems and difficulties that will appear. ❖ Get quick answers and solutions for small problems. ❖ Acquire a better idea of what to ask during interviews.
Observation of Development and Manufacturing Activities	❖ Observe directly interaction between development, planning, finance and manufacturing. ❖ Improve understanding of designer, planning, finance and manufacturing activities pertinent to relative cost calculation.
Analysis of Internal Documents	❖ Gain understanding of cost calculation systems currently in use. ❖ Describe previous cost estimation attempts. ❖ Gain understanding of cost structure and locate their data sources.
Workshops	❖ Understand different views on the relative cost estimation process. ❖ Understand difficulties and limitations of cost estimation in preliminary phase. ❖ Decide which cost estimation approach offers promise of attaining unity. ❖ Assess elaborate approaches to methodology. ❖ Gain access to data networks.
Questionnaires	❖ Acquire general survey of the need for new estimation methodology. ❖ Locate difficulties in obtaining reliable cost data. ❖ Obtain information about the time range of an actual cost calculation.
Further Dialogues (formal & informal)	❖ Speak directly with designers, planners, controller and manufacturers. ❖ Improve understanding of development and manufacturing activities. ❖ Assess elaborate methodology approaches.

Table 3.3: Objectives of data collection methods.

The use of a variety of data collection techniques permits an analysis of the entire cost estimation area together with its related processes. The sub-objectives proper to various techniques are outlined in Table 3.3. The objectives mentioned in Table 3.3 were the basis for the development of a cost-estimation methodology and a silver line for the work of data collection. Every data collection activity in Design, Planning and Finance was steered by these objectives.

Data from the R&D Centre were collected via formal and informal dialogues, group discussions, mini workshops with representatives from each department, observation of development activities, semi-structured and short ad-hoc interviews, questionnaires and analysis of internal documents. Data from the manufacturing area were collected via formal and informal dialogues, analysis of internal documents, observation of manufacturing activities and semi-structured and short ad hoc interviews, Figure 3.2.

A further important point for the extensive data collection was the chronological order of data collection techniques within the data collection process in the R&D Centre and manufacturing area, see Figure 3.2. The main period of data collection and analysis lasted eighteen months; it was followed by a second lasting six months, in which the methods of relative cost estimation already developed were presented and discussed, and more data and information were gathered, including critical suggestions for the improvement of the new methodology. The data of this second period were collected mostly by means of interviews. Once the data of the second period were analysed, improvements in the methodology were put into effect.

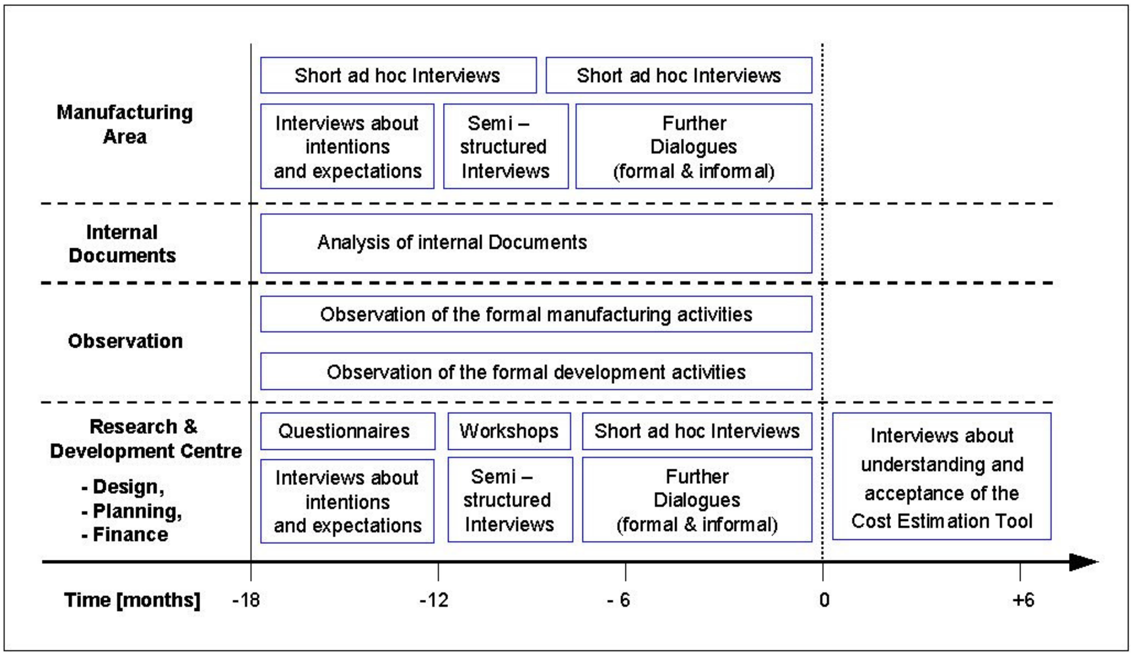


Figure 3.2: Overview of data collection methods inside the research process.

3.6 Summary

The chapter investigates feasible research methodologies for the research. For this purpose the strengths and weaknesses of quantitative and qualitative methodologies are scrutinised. Additionally different types of research methodologies with their inherent opportunities and difficulties are explained. A subsequent discussion of the research methodology points out which methodologies and techniques are relevant. It presents survey research as the most suitable technique for data gathering and also comments on the use of an industrial case study as an appropriate research strategy.

Further investigations have presented the data collection methods with their collection techniques. It is pointed out that interviews, questionnaires and analysis of internal documents are the data collection techniques most relevant to the research work.

In the last section the research methodologies previously adopted with their appropriate data collection techniques are combined in such a way as to form the research strategy. Finally there is a description of the field of application in the BMW Research & Development Centre and manufacturing area, and of the appropriate time schedule.

4 Industrial Survey

4.1 Introduction

The purpose of the present chapter is to pursue the research hypothesis by conducting a survey of the proposed research strategy. The survey will consist in the identification of pertinent literature, documentation and industrial survey findings. A questionnaire, interviews, and the analysis of internal documents are the main data collection techniques used. On the basis of the results obtained tables, sheets and matrices are elaborated that will prove to be of critical importance for the development of the Body-in-white cost estimating methodology.

4.2 Objectives of the Industrial Survey

The questionnaire, interviews and analysis of internal documents have been carried out with a focus on the following objectives:

- Identify requirements of different departments involved with the ascertainment of manufacturing costs.
- Characterise the relationship between Design, Planning and Finance regarding the transfer of cost information.
- Investigate how cost information is processed within companies.
- Identify the types of costs that are important and necessary in the Preliminary Work Phase of the development process.
- Identify the impact of a new cost estimation methodology on the decision making process within the PDP.
- Analyse the technical phases within the BIW production process.

4.2.1 Avoidance of Bias in Research

According to Rothman [2002], bias is a ubiquitous and insidious problem in the design and execution of research projects, and while no such project is exempt from it, some are more prone to it than others. Whiting *et.al*. [2004] add that "Bias is the term used to describe differences between the study findings and truth". Sica [2006] states that it is difficult or even impossible to eliminate bias completely. The effort to do so usually introduces new bias or renders the results of a project less generalisable. In the same vein Egglin and Feinstein [1996] add that readers must also be aware of the effect bias can have on validity and of ways in which it can lead to data misinterpretation and limit the applicability or generalisability of the results of a given research project. Therefore, our goal must be to minimize bias and to make both researchers and readers aware of its effects, thus limiting misinterpretation and misuse of data.

The literature pertaining to bias describes the numerous forms bias can take; in the present project the focus is on information bias. The effort to reduce that bias was one of the main factors determining the manner in which data and information were to be collected. The previous chapter dealt with the data collection techniques deemed most appropriate especially in terms of the avoidance of bias. The make-up of the questionnaire and the manner of carrying out the interviews were designed to reduce bias. The main question in the light of which the questionnaire was made up pertained to the nature of the information relevant to the hypothesis and aim of the research project. Accordingly the closed-ended questions were formulated with the help of experts in the area concerned. Hence the questions were tested copious before starting the process by sending it by Email to the participant. This was done to reduce the questionnaire bias. In addition, the answers of the participants were discussed with experts internal to the sponsoring company.

In the same way the interview outline with its questions, attached to appendix 3, was prepared in advance to insure conformity of the questions asked with the research hypothesis and aim. The questions asked in the course of the interview are specifically designed to prevent the interviewer or interviewee from digressing inadvertently from the subject. This step contributes to the reduction of interviewer bias. Results of preceding interviews were discussed with experts after completing their own interview. Obtained information and data from literature and databases were assured against bias in the same way.

Additionally the internal validation, described in section 6.3.3.1, cut down the information bias. Likewise the external validation of the obtained results, see section 6.3.3.2, by publishing, presenting and discussing results on conferences was an important step for the reduction of the bias in research.

4.3 Questionnaire

4.3.1 Aim of the Questionnaire

I order to identify current practice applicable to cost estimation of BIW design concepts it was decided to utilise a written questionnaire approach. This method was chosen in order to minimise subjectivity and provide an audit trail for the conclusions reached [Robson, 2002].

The questionnaire survey aims to evaluate the main hypothesis, which stems from the literature review in chapter 2.

Based on the final discussion of the literature review of section 2.7, the overall questions for the questionnaire survey were defined as follows.

- Is it possible for BIW designers to estimate manufacturing cost in the Preliminary Work Phase of the PDP?
- How long would it take to estimate the manufacturing costs of new design concepts?
- Will the new methodology have an impact on the BIW designer's decision-making process?

As mentioned in the previous chapter on the questionnaire, our research work includes closed-ended questions, where alternatives are given from which the respondents are to make their selections. Questions of this type allow less freedom of expression and can influence respondents. This process reduced bias by utilising a number of experts and identifying similarities and differences in their replies to the questionnaire. It is recognised that a questionnaire produces qualitative data only.

The justification for this is that the aim of the questionnaire is the acknowledgement of the need for a cost estimation methodology within the automotive industry.

4.3.2 Development and Application of the Questionnaire

The literature shows that cost estimating is a wide area and that estimation approaches could be different. For that reason it was necessary to obtain more information about the present cost estimating process in the automotive industry by means of a questionnaire.

The formulation of the questions follows the rules: "Keep the language simple"; "keep questions short"; "avoid leading questions"; etc. [Robson, 2002].

4.3.2.1 Elaboration of Questions

The lay-out of the questionnaire is divided in 2 parts. The first part contains general questions about the participant, namely his job title, the department for which he is working, and the number of years he has been working in his field. The purpose of these questions was to determine whether the participant was a professional and what his level of experience in cost estimation was.

In the second part specific questions were asked. These questions pertained to the possibility, duration, responsibility, importance and impact of the manufacturing cost estimation process in the Early Phase of the development process. Within this part it was analysed when and how cost estimation is possible. The following section elaborates on the rationale behind each of the questions. Each question was carefully designed to shed light on specific areas.

I. General Questions:

Q1: What is your job title?

This was to simply gain general background information on the precise role of the expert questioned. The author wanted to know particularly how the participant fitted into the company as a whole, in terms of his actual role.

Q2: Which department are you working for?

The author wanted to know particularly in which area cost estimators in the company involved are engaged so that it could be identified where the competence of cost estimation is located.

Q3: For how many years have you been working in that field?

It should be made clear whether the participant was to be rated as an expert or a newcomer in the area of cost estimation.

II. Specific Questions:

Q4: Is it possible for your department to estimate manufacturing cost for a new Body-in-white design at the preliminary phase by using an appropriate method?

This question was asked to obtain a clear view if any proper methodology is available for the manufacturing cost estimation of new BIW concepts in the Early Phase of the PDP.

Q5: In which phase of the Product Development Process can you normally begin cost estimation for a new design?

The aim of this question was to find out in which phase of the PDP methodologies for cost estimating are available for assessment of new BIW design concepts.

Q6: If a new BIW design concept is available, how long would it take to estimate the manufacturing costs?

Considering the duration of manufacturing cost estimation, Q6, concerned with the amount of time required for estimation of manufacturing cost, asks how long it would take to estimate manufacturing costs if a new BIW design concept is available. The aim of the research project will be to expedite this process.

Q7: surveyed the participants on the question what data sources available to the cost estimator enable him to proceed with the estimation process.

The aim of this question was to see which departments cooperate with the cost estimator in the standard cost estimation process internal to the company. This information throws light on the degree of cooperation between the design, planning and finance departments in cost estimation.

Q8: Which of the departments mentioned in Q7 provide data of critical importance for your cost estimate?

The author wanted particularly to find out from the point of view of the participant which departments hold the data relevant to his cost estimation of new BIW design concepts. The aim of this question was to ascertain which departments should work together in close collaboration and which is the most important partner for the designer who is making the cost estimate of new concepts.

Q9: Could you indicate your confidence level in the information obtained, using the scale below?

The purpose of this question was to gain clarity on participant confidence in the data obtained from the departments cooperating i.e., on the question whether the quantity and quality of the data permit significant results in cost estimation.

Q10: How long does it take to obtain the information from the data source?

The aim of this question was to ascertain the amount of time required to obtain information from the experts of Finance, Planning, Design and Manufacturing that are necessary for cost estimation.

Q11: Can you rank using a scale from zero to a hundred the importance of having a new tool for a rough manufacturing cost estimate in the Early Phase of the development process?

In this context, Q11 was formulated with the aim of gathering information about the need for every department to have a new methodology for BIW manufacturing cost estimating in the preliminary work phase.

Q12: Do you expect this new tool to have an impact on your decision making process?

As an extension of Q11, Q12 inquires into participant expectations with a view to determining the way in which the new methodology might have an impact on their decision making process.

Once the questionnaire had been designed, it had to be tested, e.g. with colleagues and experts from the sponsoring company, so that the design might be optimised.

In fact, the total survey process was tested, from the initial contact with the participants via telephone to the ways of sending the material to participants and the actual filling out and returning of the questionnaire. When the questionnaires were returned, the analysis of the responses was also tested, the purpose being to ensure that the structure and questions of the survey provided sensible data in terms of the aims and objectives of the survey. The final questionnaire is enclosed in appendix B of the thesis.

4.3.2.2 Approach of Potential Participants via phone

The companies were approached by telephone, with the researcher using a standard introduction to introduce the survey and to identify an interest in the potential participant.

In accordance with the recommendations of Floyd [1993] and Thomas [1996] the survey was introduced as a "research project" in which participation is sought. The target number of participants for the questionnaire survey was about 200 persons in the leading automotive companies: Audi, BMW, Mercedes and Volkswagen. These companies were chosen in accordance with the need to investigate a wide range of car producers, from, on the one hand, manufacturers of premium cars like BMW with around 1 million units per year, to car manufacturers for the mass market, on the other, like Volkswagen with around 4 million units per year (data of the year 2006).

The worldwide network of automotive companies has engendered contacts amongst design, planning and finance departments beyond the sponsoring company.

The questionnaire was sent to the BIW design, planning and finance departments of these four automotive companies.

It was explained to participants what was required of them; they were also told the reasons why particular companies were chosen and where the names, addresses and telephone numbers of the contacts came from. Furthermore, the benefits of participation were explained.

Once the research was explained and questions were answered, the person contacted was asked whether he or she would be interested in participating. In the event of a positive answer, the option of an electronic questionnaire sent by e-mail or of a printed questionnaire was offered.

Sending of Questionnaire

Following a positive answer, the questionnaire was sent out in the format agreed upon. The timescales agreed upon for questionnaire returns were monitored by means of a spreadsheet, and the participant's organisation was contacted if the questionnaire had not been returned within a few weeks after the promised return date.

4.3.2.3 Data Analysis

Returned questionnaires were analysed in the following way:

- Questionnaires were checked for completeness and general approach to filling out (high-level quality check).
- Responses were given a detailed analysis, and the data obtained were transferred into a data analysis spreadsheet.

In some instances, where the responses were incomplete or not understandable, or where an interesting point was raised, the participants were contacted again for clarification or for further details.

4.3.3 Questionnaire Findings

In the following section, the findings of the survey are presented and discussed.

4.3.3.1 Basic Questionnaire Survey Statistics

For the questionnaire survey, 180 persons occupied in twelve departments belonging to four companies participated in the questionnaire survey. This was a response rate of 89%. Of those that did not participate, nine declined when first approached.

A further six declined participation after looking at the survey. Seven participants agreed to participate, but did not return the questionnaire. In all but two cases, the reason given for non-participation was a lack of time.

The original target number of participants (minimum of 200, maximum of 250) could not be reached because of lack of time. However, analysis of the responses received made it clear that the 180 who did participate were numerically ample for the purposes of the survey.

The outcome of the questionnaire survey is reviewed in the following section. The individual questions were numbered Q4 through to Q12.

4.3.3.2 Outcome of the Questionnaire Survey

On the basis of the objectives of section 4.2 the questions generated the following results.

Q4: Is it possible for your department to estimate manufacturing cost for a new Body-in-white design at the preliminary phase by using an appropriate method?

The possibility for the design departments to estimate manufacturing cost for a new BIW design concept at the preliminary phase of the PDP by using an appropriate method was rated below 20%. Slightly less than 20% of the participants thought it possible for design departments to estimate the manufacturing cost of a new BIW design concept by application of a reliable method at the preliminary phase of the PDP. Those who did were from design departments, were able to estimate the cost of new BIW design concepts in the preliminary phase, and had worked in their field of activity for at least eight years. Between 70 to 80% of the respondents from the Planning departments stated that they have no appropriate method for cost estimation of a new design concept at the Preliminary Work Phase. Also, 50% to 60% of the informants from the finance departments were unable to effect cost estimates in the preliminary phase of the PDP. The results of Q4 made it clear that the lack of a proper cost estimation methodology is not a problem of the design departments alone. A great number of planners and members of the finance departments are also unable to carry out cost estimation of a new BIW design concept in the preliminary work phase. 87% of the participants who claimed to have the possibility for cost estimation in the preliminary phase have been working in their present capacity for at least eight years.

Q5: In which phase of the Product Development Process can you normally begin cost estimation for a new design?

The inquiry showed that of about 40% of designers, the majority are unable to initiate cost estimation until the beginning of the maturation phase.

On average, 20% of designers interviewed are capable of doing cost estimation in the confirmation phase. Another 10% can start the estimation process in the coordination phase. The majority of approximately 40% of the planners can achieve a cost estimation result in the coordination phase. Around 20% of them can start the estimation process in the preparation phase, which is at the end of the preliminary work phase, see section 2.3.1. The responses of the finance department members are comparable to those of the designers. The majority can start in the maturation phase. At this stage of the PDP, the process of cost estimation is mostly a process of cost calculation. Like Q4, Q5 shows that there is no proper methodology for the majority of cost estimators in the preliminary work phase.

Q6: If a new BIW design concept is available, how long would it take to estimate the manufacturing costs?

The designer requires the longest time with 12 to 24 weeks for the estimation of a new design concept. Within this time range, the minority of the respondents from the design departments have to wait for more than 16 weeks until they get the result of the estimation. Only around 20% of the designers will get a faster result in the time range of 12 to 16 weeks.

Approximately 40% of the participants from the design departments have to wait more than 20 weeks for a preliminary result.

The information received with Q6 verified the statement, as indicated in section 2.4.2, that the "long" control loop is a time consuming process and a "short" control loop can be achieved through the intensification of collaboration between design and the other relevant departments.

Q7: Surveyed the participants on the question what data sources available to the cost estimator enable him to proceed with the estimation process?

With approximately 40% of the votes, the statistics show that the most important partner for the designer about proceed with cost estimation is the planning department. Coming in a close second with 20%, the finance departments occupy a position of pre-eminence for the designer involved in the cost estimation process. As a "connector" between Design and Finance, the planner is dependent on each of the other two departments for around 40% of his data.

That finance departments rely mostly on data from planning departments is evident from the result of more than 50%. The above-mentioned conclusions show that every single department is more-or-less dependent on information from other departments involved in the development process. This validates the conclusion of section 2.4.3 that the intensification of collaboration between Design, Planning and Finance is of critical importance.

Q8: Which of the departments mentioned in Q7 provide data of critical importance for your cost estimate?

The different design departments indicated the importance of data flows between their own departments and the planning and finance departments in around 70% to 90% of cases.

From the designer's point of view, with around 20% weighting, the cost estimation is accomplishable without intensive involvement from the manufacturing department. This finding shows the opinion current within design departments that the planning departments are more closely connected to the manufacturing departments than their own departments. This becomes apparent from the appraisal of the information of the participants from the planning departments. The importance of data flows between the planning departments and the manufacturing departments was indicated in 50% to 70% of the cases. Also, the collaboration between the planning departments, on one side, and design and finance departments, on the other, is revealed by the result of the analysis of answers on the scale of 80% to 90%. This validated the above-mentioned statement that the planning departments are “connectors” between the design, finance and manufacturing departments. Also, the opinion of the finance department becomes clear after the evaluation of their responses for Q8 that in 80% to 90% of cases the planning departments are the most important data source for their cost estimation process. In 50% to 80% of the cases, the design departments are behind the planning departments. The manufacturing departments have, with 40% to 60%, not the highest importance for data flow for the purpose of cost estimation, from the point of view of the finance departments. The information acquired in Q8 may be taken as evidence supporting the afore-mentioned hypothesis, that collaboration between the departments concerned is an important condition of effective cost estimation of new BIW design concepts.

Q9: Could you indicate your confidence level in the information obtained, using the scale below?

Further valuable information was discerned in answers to Q9, which on a scale of 50% to 100% show the level of participant’s confidence in the information or data obtained. The design department judges a level of 50% to 60% confidence in the information obtained unsatisfactory. The planning departments expressed their dissatisfaction with a confidence level of 60% to 70%. Analysis of the answers given by the finance departments indicated that this amounts to a call for action to improve the level of confidence in the data obtained.

Q10: How long does it take to obtain the information from the data source?

The majority of the respondent departments admitted that the normal process of data acquisition takes more than 4 to 8 weeks. Whereas, the design departments’ answers incline more to the statement that the data gathering process takes more than 8 weeks. The resume of Q9 and Q10 amounts to a call for action to raise the level of confidence in data obtained and to reduce the length of time required for obtaining information. The contentment of the departments involved is low and the demand for improvement high. This demand is further evidence that research must develop a methodology capable of providing BIW engineers with a comparative estimate of manufacturing costs for different design options.

Q11: Can you rank using a scale from zero to a hundred the importance of having a new tool for a rough manufacturing cost estimate in the Early Phase of the development process?

The design departments rank the importance of this subject with an approval rate of 90%. The planning departments follow with a rate of 80% to 90%. Only the finance departments, with 60% to 80%, gave the impression that the need for a new methodology within their department is not of critical importance. This statement can be interpreted in light of the fact that the finance departments have cost calculation tools for cost estimation.

These tools, as already is known from section 2.5.3, are based on the quantitative methods for cost-effective designing that cannot be utilised in the preliminary work phase.

Q12: Do you expect this new tool to have an impact on your decision making process?

The fact that the design department confirmed this statement with 90% in favour means that the new methodology will have a greater impact on their decision making process. With 80% to 90% in favour, the planning department gave their approval for Q12.

In keeping with their response to Q11, the finance department responded to Q12 in a manner suggesting that they would not expect development of a new cost estimation methodology to have an important impact on their decision making process. This result is based on the fact pointed to in the discussion of Q11. In conclusion, Q11 and Q12 make it apparent that mostly the design and planning departments have a stake in utilising a new cost estimation methodology.

4.3.3.3 Summary of the questionnaire findings

The findings of the questionnaire show how the design, planning and finance departments perceive the prevailing cost estimating process of BIW design concepts.

Thereby the focal points were the starting point and duration of the estimation process, and especially the importance of collaboration between the departments involved in the Product Development Process.

The need for and the importance of a new cost estimation methodology were confirmed by all three of the departments questioned. Aside from the findings presented in this section, the results yielded by analysis of responses to the questionnaire are presented in charts and attached in appendix 2 of the thesis.

4.4 Interviews

In addition to the questionnaire, interviews were conducted with members of the design, planning and finance departments. The interviews complemented the results from the questionnaire survey. Face-to-face interviews were used as the main data collection method, although a number of telephone interviews were also conducted. The number of interviewees and the time of interview are difficult to specify because of the great number of short ad-hoc interviews and the hierarchical distinctions of participants within the company. The semi-structured or standardised approach was used for both classes of interviews. Unlike the questionnaire survey, interviewing was conducted mainly by way of open-ended questions, which make it possible to gather more knowledge from experts. In all, around 80 interviews were conducted at BMW in two years.

4.4.1 Aim of the Interviews

In addition to the objectives of section 4.2, the following objectives of the interviews will provide a basis on which to

- validate the research hypothesis.
- obtain evidence for existing internal documents.
- investigate the interfaces for data exchanges.
- evaluate the approach to cost estimation within departments.
- evaluate the importance of a cost estimation methodology in the preliminary work phase.
- identify the technical complexity in the BIW production process.
- analyse the alteration of material combinations in the BIW design process.
- identify and analyse the coherence between WC’s and JT’s.

4.4.2 The Accomplishment of the Interview Survey Operation

The realisation of such a great number of interviews over a period of two years required the partition of interviewees into several groups. The first group contains all participants who are associated with the design departments. The second group comprised the planning departments with their neighbouring departments, and the third and last group represents the sector of the finance departments, see Figure 4.1.

In the process of conducting interviews, new contacts were made with experts involved in the process of cost estimation. These experts supported the development of a new BIW cost estimation methodology by making comments on the practical applicability of the method. These experts were working in Design, Planning and Finance. Weekly interviews in their departments resulted in illuminative information and results. This information and data were classified at the start of the research into topics. The first topic contained general information about the development process. The second topic was concerned with technical information and data that are relevant in analysing and converting the specification data of a new design concept into WC's and, afterwards, into JT's. The third topic dealt with information pertaining to cost structures, cost detection and cost calculation.

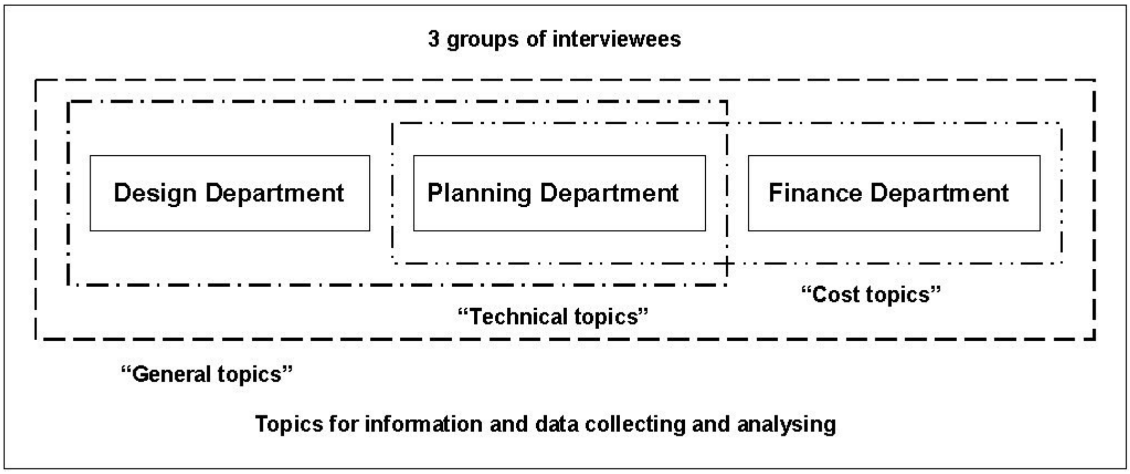


Figure 4.1: Classification of interviews and topics.

An interview outline with questions taken from these three topics and relevant to the later development of the cost estimating methodology assured the standardised interview process described in Chapter 3. This interview outline and its results are attached to Appendix 3.

The main results of the interviews conducted during the long period in which the research project was carried out are summarised in the following sections.

4.4.2.1 General Topics

1a) Is there a need for a cost estimation method in the Early Phase of the PDP?

The majority agreed that there is a definite need in the company for a cost estimation method in the preliminary work phase. The interviewees described the characteristics of these methods in a way not essentially different from that of the descriptions obtained in the questionnaire survey.

1b) Are Body-in-white designers unfamiliar with cost decision methodologies?

With respect to the design process, 100% of interviewees admitted that although the BIW designer is expected to have the expertise required to apply JT's to new design concepts, the designer may not be familiar with cost decision models and corresponding optimisation procedures. The director of the BIW design department indicated that while the designer has the expert knowledge and appropriate software tools for optimising his design concept in all technical respects, the designer cannot be helpful with respect to cost estimation methods.

1c) Can Working Contents be used as a "common denominator" between Design, Planning and Finance?

When on the basis of the interviews the complexity of the BIW engineering process was analysed, it became apparent that WC's could be used as a "common denominator" between Design, Planning and Finance. Around 90% of the respondents corroborated this sub-hypothesis and took it as a fact that they can link their process parameters with WC's.

1d) Can Working Contents be transformed into Joining Techniques?

Nearly 90% of the interviewees agreed to this essential technical and economic coherence. They approved the statement that it is possible to mathematise and standardise Joining Technologies.

1e) Can Joining Techniques establish a basis for the BIW cost estimation methodology?

This statement was accepted by around 90% of the interviewees, irrespectively of the department for which they were working. Over 95% of the manufacturing process arising from a BIW design consists in joining processes that dominate the manufacturing cost.

1f) Does the material of the joining process play an important role in the manufacturing and cost estimating process?

The majority of the interview participants accepted this conclusion. The material used determines which joining techniques are appropriate in terms of both technical and economic aspects. Hence the choice of material has a significant impact on the manufacturing cost estimating process. The problem of choosing the right Joining Technique in terms of costs and technical aspects is complex and therewith exceedingly difficult to deal with.

4.4.2.2 Technical Topics

2a) Do you agree with the research hypothesis: "It is possible to develop an estimating method on the basis of information contained in the specification data of BIW design concepts."?

The research hypothesis, elaborated from findings of the literature review, was confirmed by the majority of the design and planning departments. Members of the finance departments could not give information about this hypothesis because they are not sufficiently involved with BIW specifications. Especially the designer strongly supported this hypothesis because specifications stand in the centre of their daily work. Also the planning department agreed without exception to this statement because they have to develop the production line in accordance with the parameters of the specification data.

2b) Can the data content of the specifications be converted into Working Contents?

The majority of the design as well as the planning departments support this conclusion. They confirm the connection between BIW design drawings with their specification data and the mathematical conversion into Working Contents that in the next step are to be transformed into Joining Techniques. All interviewees agreed that this connection is of paramount importance if a method enabling the BIW designer to compare different new BIW design concepts with one other in the Early Phase of the PDP is to be generated. Most respondents gave important information and provided access to existing data and documents.

2c) Does the Body-in-white designer have the technical expertise to apply Joining Techniques to BIW design concepts?

The design department confirmed this statement univocally. In completing their design concept they had to allocate suitable Joining Techniques to the Joining Sides in accordance with the technical requirements. This task belongs to the responsibility of the designer but is supported by the planning department with relevant information. The planning department can accept a given design unhesitatingly because they were involved in its development.

2d) Is the Body-in-white designer able to identify the optimal combination of Joining Techniques of a design concept in terms of cost?

In the opinion of 95% of BIW designers, design procedure has always felt compelled to hold itself aloof from consideration of cost. Upon completion of the BIW design concept as a whole, the designer has to fragment the concept into individual sheet metal components, which must then be joined. At this point the designer is too swamped with decisions pertaining to the optimal combination of JT's to pay serious attention to the manufacturing cost thereby incurred. For this reason everyone agrees that the design department has no expertise enabling them to determine the optimal combination of Joining Techniques of a given design in terms of cost.

4.4.2.3 Cost Topics

3a) Can you estimate the manufacturing cost of new Body-in-white design concepts in the Early Phase of the Product Development Process?

Over 80 % of interview participants answered this question in the negative. They argued that in the preliminary phase of the BIW Product Development Process there is a lack of data required for an early cost estimate. At present no cost estimating methodology is available that can help the BIW designer in his decision making when he is selecting from competitive BIW design concepts.

3b) Is the major portion of the manufacturing cost of a Body-in-white design concept located in the Joining Technique process?

Planning and Design felt strongly that the major portion of manufacturing cost is found in the Joining Technique manufacturing process. They specified that 90% of the total costs in the BIW production area are associated with Joining Techniques and the pertinent equipment.

3c) Are relevant Joining Technique cost data available?

Analysis of the interviews and of pertinent documents led to the result that no detailed and structured Joining Technique cost data that could be helpful for an early cost estimate of BIW design concepts are available. Over 90% of Finance on one hand and Planning on the other acknowledged the lack of completed and detailed Joining Technique cost templates pertinent to the BIW manufacturing process.

3d) Are the available cost data reliable?

More than 50% of the interviewees from Finance and Planning admitted that the sparsely available cost data pertaining to Joining Techniques are unreliable and not updated. The rest of the interview participants spoke of long experience in their field of work that enables them to appraise reliability of the present cost data.

4.4.3 Summary of the interview findings

The basic findings of the interviews largely confirmed the results of the questionnaire. The outcomes of the interviews pertaining to general, technical and economic topics corroborated the research hypothesis that it is possible to develop a cost estimating method on the basis of information contained in the specification data of BIW design concepts. The interviewees revealed the lack of a cost estimating method in the Early Phase of the BIW Product Development Process. In addition it was pointed out that at present it is impossible for the BIW designer to estimate the manufacturing cost of a new design concept. It was generally agreed that Working Contents can be used as a "common denominator" between Design, Planning and Finance, and be transformed into Joining Techniques. These make up over 90% of the BIW manufacturing cost. Joining Techniques in coherence with Working Contents are to establish the basis for the BIW cost estimation methodology. Additionally the interviews revealed that there are no proper and detailed Joining Technique cost data that can be used for the early cost estimating process of BIW design concepts.

4.5 Analysis of Internal Documents and Literature

Contemporaneously with the process of interviewing, the process of analysing internal documents and literature was carried out by the researcher. Access to data banks and actual project servers was obtained by Experts and project managers who were contacted in face-to-face interviews and project-work. These data have to be scoured for information, which can be used in the methodology of the research work. The difficulty of data mining and of extracting proper data from the data banks and project servers was solved by means of interviews with experts.

4.5.1 Aim of the Analysis of Internal Documents and Literature

The most important aim of the analysis of internal and external company documents was the extraction of pertinent data. In addition to the industrial survey objectives listed in section 4.2, the following objectives of the analysis of internal documents and literature have been considered in order to

- analyse information about Working Contents.
- analyse the material demand for the BIW design process.
- analyse the Joining Technique process.
- analyse the connection between WC's and JT's in the BIW design process.
- investigate the quantity of sheet metal components required for the car body.

These objectives based on the outcomes of the concurrent interviews.

4.5.2 Analysis of internal documents and literature

In the course of the survey the researcher was given access to internal documents and databases thanks to the mediation of experts and persons competent in Design, Finance or Planning. The data were discussed and evaluated with these experts, and were then cast in a form useful for the overall research aim, which is to develop a BIW cost estimating methodology. In these wise tables, sheets and matrices of fundamental importance to the methodology aimed at were developed; they are described in detail in section 4.6. It was noted that the nature of this information places it well within the sponsoring company's guidelines on data publication.

Analysis of these data gradually brought to light information pertinent to the general understanding and use of Working Contents. On the basis of this information a mathematical definition of a BIW Working Content was generated, see 4.6.1. This definition, a key element in the development of the cost estimating methodology aimed at, opens the possibility of comparing various design concepts in terms of the respective numbers of Working Contents involved, hence in terms of cost. In addition it became apparent that the development of a Standardised Working Content Coefficient, see 4.6.1.1, is indispensable if various Joining Techniques are to be ranked qualitatively. On the basis of this coefficient, comparison of BIW design concepts becomes possible in qualitative terms.

Similarly data pertaining to the technical relationships between joining materials and Joining Techniques was analysed and arranged by the researcher in a matrix of approved Joining Techniques and material combinations. This matrix, which represents in concentrated form the present state of relevant knowledge, makes it possible for all technically possible material combinations on the one hand and all approved Joining Techniques on the other to be surveyed simultaneously, providing therefore an indispensable asset to the user of the cost estimating methodology.

Examination of the joining process in the BIW production showed that for a realistic BIW cost estimating process it is of critical importance to take account of the contour and condition of the sheet metal surfaces to be joined. To deal with technical constraints the researcher elaborated a Joining Side Coefficient based on the following five criteria. 1.) thickness of sheet metal, 2.) width of the joining cross section, 3.) appropriate surface condition, 4.) accessibility of the joining zone, and 5.) contour of the joining part. All of these criteria affect the cycle time of the technical joining process and therewith the BIW manufacturing cost. On the basis of these criteria Complexity Sheets were developed, itemising the technical difficulties that appear when two metal sheets are to be joined together. The Complexity Sheets consider the variations of the cycle time and compensates for them by the Joining Side Coefficient.

The last extensive step during the interviews and analysis of internal documents and literature entered the area of Joining Technique cost data. Due to the fact that internal documents, literature and results of intensive interviews did not provide sufficient cost data relevant to the cost estimating methodology, the decision was made to develop cost templates tailored to BIW cost estimating. A detailed analysis of cost data, centred especially on Joining Techniques, was conducted in this research project. This analysis, supported by the finance and planning departments, revealed the main cost-driving factors. Expanding the interviews into the manufacturing area made it possible to collect reliable cost information, including cost data, which was then analysed. The data arrived at by the cost analysis of Joining Techniques were verified with the help of the finance and planning departments. Subsequently these data were structured into a specially elaborated Joining Technique Cost Template, which can be found in Appendix 5. A template was generated for every Joining Technique with its approved material combinations. These templates indicate in detail the total investment and manufacturing cost for each Joining Technique. Finally the total cost of a JT could be expressed mathematically as a Working Content, which is the smallest unit of work.

4.5.3 Summary of the internal documents and literature findings

In the contemporary processes of analysing internal documents and literature on one hand and conducting interviews on the other it became apparent that pertinent data and information has to be filtered and concentrated into tailored tables, matrices and templates. Hence the generating of a mathematical definition of a BIW Working Content with its standardising process was carried out as an essential step in the development of an overall BIW manufacturing cost estimating methodology. Subsequently the technical interrelationships between joining materials and Joining Techniques were analysed and expressed in a matrix. This matrix opens the possibility of selecting the approved Joining Techniques with their material combinations on the basis of technical criteria. Similarly the BIW manufacturing process was scrutinised and the variation of the cycle time of the BIW joining process, caused by technical factors, was revealed. Thereupon Complexity Sheets were elaborated to indicate the various BIW part contours that influence the cycle time. To compensate for the resultant cycle time variations, a Joining Side Coefficient was introduced.

The concluding analysis led into the area of cost data. Due to the fact that sufficient and significant Joining Technique cost data were not available, Joining Cost Templates were elaborated on the basis of Joining Technique investment and manufacturing cost.

Finally the total cost of the JT was expressed mathematically as a Working Content which is the smallest unit of work.

The following section 4.6 elaborates at full length the previously described tables, matrices and templates that were of prime importance for the subsequent development of the BIW manufacturing cost estimating methodology in Chapter 5.

4.6 Elaboration of Data and Definitions relevant to the Development of the Body-in-white Cost Estimating Methodology

4.6.1 The Definition of Working Contents in the BIW design process

Practical examples and various interviews confirm the hypothesis that BIW component drawings can be associated with a definite number of WC's. Such a reduction is useful because the number of WC's actually carried out is what determines the added value of a product.

It became apparent that neither in the literature nor in the documents internal to the various companies was a definition of a Working Content suited to BIW cost estimation available.

The interviews showed that every Joining Technique can be expressed as an integral number of Working Contents. A Working Content is therefore the smallest or the elementary unit of work in BIW production, which is interdependent to the cycle time. In addition interviews showed that a mathematical definition of a Working Content is indispensable for a new BIW cost estimating methodology. The interviews also made clear that the main part of the total BIW manufacturing cost is traceable to the technical joining process, within which the JT's are by far the most important factor driving up production costs. For this reason the mathematical definition of a Working Content is the basis of the BIW manufacturing cost estimating methodology.

Mathematical Definition of a Working Content

As already mentioned every WC of a given JT corresponds to a definite cycle time. A WC can equally well be given a technical definition in terms of joining length. Every design concept can be broken down into individual components that must be joined together, a fragmentation that can be carried out with the help of CAD programs. Subsequently the individual JS lengths are assessed. Henceforth the number of WC's can be calculated on the basis of the individual JS lengths. Enquiries, data acquisitions and calculations within the BIW joining process of the automotive industry indicate that a JS length is conveniently partitioned into 50mm sections. This gives rise to the following definition.

$$\text{Number of WC's of examined JS} := \frac{\text{total length of JS examined}}{50\text{mm}} \qquad (4.1)$$

Solutions with non-integral values must be rounded off because only whole WC’s can be carried out; welding spots or punch rivets are examples. Based on this rounding-off rule the cost estimation will be on the safe side because in the worst case the total theoretical number of WC’s of a BIW design concept is higher than the real number of WC’s. In consequence of this the result of the subsequent cost estimation, which is a function of WC’s, will also be higher, so the Designer will not underestimate the cost for his BIW design concept. With the help of this definition, which is valid for every BIW design concept, the amount of time and material required for 50mm joining can be allocated to every JS, provided the particular combination of joining materials be taken into consideration. This new mathematical definition of a WC is fundamental for the development of the BIW cost estimating methodology presented in Chapter 5.

The introduction of WC’s into the BIW Product Development process is that of a technical and economic constant from which every department involved can benefit.

A) The designer knows that the individual parts of his BIW design concept have to be joined by means of JT’s that can be expressed as a definite number of WC’s. Hence the designer can calculate the total number of WC’s both during and after the design process for every BIW concept, and by comparing the different concepts he can decide which is best in terms of cost.

B) The planner knows that a concept for a BIW production line has to be elaborated with the aim of getting optimal cycle time. Because of the mathematical relation between the WC’s of the Joining Techniques and the cycle times the planner can readily calculate the cycle time of every BIW design concept and can use it to work out the cycle time diagram.

C) The finance department knows that a certain number of cycle times are needed to manufacture the scrutinised BIW design concept. As the number of WC’s can be ascertained, the designer can now calculate in advance the manufacturing cost on the basis of the JT Cost Templates of the design under consideration. These templates are introduced in section 4.6.4.

As the interviews revealed, WC's act as a "link" between the design and production process. It was pointed out in section 2.4.3 that they serve as a "common denominator" between the design, planning and finance departments, thus enhancing significantly interaction between them. Hence a WC is a technical and economical standard of measure, a constant value that can be used by the above-mentioned departments.

4.6.1.1 Elaboration of the Standardised WC Coefficients Table

Once a WC has been given a general definition suited to meet the functional requirements of Design, Planning and Finance it becomes possible to work out the additional details. The fact that in terms of time and material expended one WC of spot welding is not equal to one WC of laser welding means that a standard WC must be found. For this purpose one fundamental JT must be fixed upon as a basic unit with reference to which all others can be measured. An analysis of interviews and internal documents suggests clearly that spot welding of steel to steel is best suited as a unit of reference. As spot welding is currently the most frequent JT and steel with steel the most frequent combination of materials joined in automotive BIW production, the data involved have been most thoroughly evaluated and are hence most reliable for research purposes.

This unit of reference coupled with the data of the JT cost templates, elaborated in section 4.6.4 and attached in appendix 7, makes it possible to generate a standardised WC coefficient (SWCC). This coefficient is calculated from (1) the absolute value of investment and (2) the manufacturing cost of each JT for one WC of any material combination divided by the absolute value of investment and manufacturing cost of one WC of the reference basis, in our case spot welding of a steel – steel compound. A calculation example for the SWCC of MIG welding paired with the material combination aluminium - aluminium yields the following result as indicated in equation (4.2).

$$SWCC_{\text{MIG welding}_{\text{alu-alu}}} := \frac{c_{\text{MIG welding}_{\text{alu-alu}}} + M_{\text{MIG welding}_{\text{alu-alu}}}}{c_{\text{Spot welding}_{\text{steel-steel}}} + M_{\text{Spot welding}_{\text{steel-steel}}}}$$

$$= \frac{0{,}00685 \text{ EUR} + 0{,}01856 \text{ EUR}}{0{,}00531 \text{ EUR} + 0{,}01137 \text{ EUR}} = \frac{0{,}02541}{0{,}01668} = \underline{\underline{1{,}52338}} \tag{4.2}$$

c := investment cost of Joining Technique, see respective cost template.

M := manufacturing cost of Joining Technique, see respective cost template.

This calculation shows that the SWCC is the ratio of cost for one WC of MIG welding expressed as a function of one WC of spot welding. By means of this standardisation to remaining JT's a table of SWCC is provided as shown in Table 4.1. The appending calculation of SWCC is attached in the Appendix 4.

Joining side Material:		Steel - Steel	Steel - High tensile Steel	Steel - Aluminium	Aluminium - Aluminium	Aluminium - High tensile steel
No.	Joining Tech. / SWCC	$SWCC_{st-st}$	$SWCC_{st-htst}$	$SWCC_{st-alu}$	$SWCC_{alu-alu}$	$SWCC_{alu-htst}$
1.	Spot welding	1,00000	1,38525	--	1,33429	--
2.	Spot weld-gluing	8,60971	10,94125	--	--	--
3.	MIG welding	1,36391	1,58100	--	1,52338	--
4.	Tandem MIG welding	1,20516	1,45174	--	1,30438	--
5.	MAG welding	1,61613	1,72482	--	1,44856	--
6.	WIG welding	2,79724	--	--	2,93645	--
7.	Laser-welding (CO_2)	2,26319	2,42446	--	2,37890	--
8.	Laser-welding (Diodes)	2,80396	2,97776	--	3,38261	--
9.	Laser-welding (YAG)	1,49053	2,44005	--	1,84874	--
10.	Projection welding	1,11241	1,21475	--	--	--
11.	Laser brazing	2,92506	--	2,98261	--	3,07674
12.	MAG brazing	1,77698	--	--	--	--
13.	Punch riveting	2,33729	--	2,52002	2,47206	2,86427
14.	Blind riveting	2,55168	2,96085	2,82740	2,57218	2,79910
15.	Clinching	1,47314	--	1,72896	1,38327	1,97734
16.	Flanging	2,84329	3,31055	2,99976	2,90180	3,28333
17.	Cohesiveness gluing	2,08273	2,34970	2,49947	2,61679	2,45857

Table 4.1: Standardised Working Content Coefficients table.

With the help of this SWCC table, the designer can obtain the total sum of standardised WC's (SWC's) for his new BIW design concept. This sum of SWC's specific to a single BIW design concept gives illuminating information about the technical and economical rating of a new design concept. Likewise the cost calculation of an already known combination of JT's required by a BIW design concept is made possible by the SWC's, which will be treated in Chapter 6.

With the formulation and implementation of WC's a number of research objectives of section 1.3.3 have been reached, though perhaps only tentatively. Hence it is possible to make an accurate cost calculation of an actual design concept by the means of WC's. To achieve the research aim of providing the BIW design department with a methodology capable of effecting cost comparison of different future design concepts in the Early Phase of the PDP, it will be helpful to find the optimal cost of the design concepts under scrutiny. Therefore an important further step in research will be to provide a method for including accurate cost estimates in finding the optimal JT combinations in terms of manufacturing cost. The methodologies and considerations necessary for this are discussed in chapter 5.

4.6.2 Elaboration of a Matrix of approved Joining Techniques and Material Combinations

The interviews and the internal documents made it apparent that the choice of an approved JT for a given material combination is an important pre-step in the BIW manufacturing cost estimating process. This means that when a given combination of materials has been determined, the BIW designer must select the technically appropriate joining technique. This process of choosing the right Joining Technique in terms of technical aspects is complex and therewith exceedingly difficult for the designer.

For this reason a matrix of approved JT's and material combinations was elaborated, the purpose of which is to facilitate the designer's choice.

It was pointed out in section 2.3.2 that an important goal of automotive BIW design is the reduction of car body weight and, consequently, of fuel consumption. One of the most important ways of reaching this end is the use of lightweight materials. Consequently, the use of composite design plays an important role in the weight reduction of the vehicle body. The demand placed on the design and planning departments by this perception is to find new and lighter materials that meet the technical requirements of mechanical strength, stiffness, corrosion resistance, durability etc. These new materials require in turn new JT's with a high degree of process stability.

	1998 Serial production	2003 In addition to Serial production	For the future In addition to the serial production
High number of units	- Steel in integral monocoque constructions		- Steel hydroforming - High-tensile steel
Medium number of units	- Aluminium-steel composite technology	- Steel hydroforming - High-tensile steel	- Aluminium-car body shell
Low number of units	- Aluminium-car body shell	- Aluminium-structure in frame mode of construction	- Carbon fiber reinforced plastic
Alternative Steel-grade	- DC-metal-grade ZE ordinary steel - BH-metal-grade ZE micro alloyed steel	- 5000 steel, 6000 steel - TMS 1300 - CP 800 - DC-metal-grade Z100 ordinary steel - BH-metal-grade Z100 micro alloyed steel	- DP-steel - TRIP-steel
Alternative Joining-techniques	- Resistance-spot welding - MAG-welding - Studs-welding - Laser-welding - Gluing - Crimping - Stamping riveting - Clinching - Hemming	- Resistance-spot weld-gluing - Friction welding - Hemming adhesive - Aluminium MIG welding - Aluminium stamping riveting - MIG brazing	- Plasma-welding - 2C-gluing - Stamping rivet-gluing - Laser brazing

Table 4.2: Alteration of Joining Techniques and material combinations.

Table 4.2 gives a general overview of the alteration of the material on the one hand and the JT's on the other.

It is apparent that in future BIW production the composite of steel and aluminium will have the upper hand because of comparatively light weight design. Additionally high-tensile steels are coming up today in BIW design. These new material composites increase the number of material combinations and of the attendant Joining Techniques.

For the compilation of the required data, essential for the BIW cost estimating methodology, a new matrix of approved Joining Techniques and material combinations was elaborated by the researcher. For that purpose data from: a) data bases, b) internal documents, and c) literature were analysed and filtered. In close collaboration with experts from the planning and manufacturing departments the consistency of these data was verified.

This matrix, see Table 4.3, give in concentrated form the present information on material combinations and the approved joining techniques used in BIW manufacturing. The Joining Techniques are arranged in rows and classified in three groups: a) warm

JT's, b) cold JT's and, c) gluing. The material combinations are arranged in columns that indicate whether a given JT is approved or not. During the design process, the designer can decide whether his choice of JT will lead to technical problems in the future or not. Therewith the designer can ascertain which Joining Technique is approved for the serial production of his selected material combination. This matrix is to be updated at regular intervals by the planning department.

Matrix of approved Joining Techniques and material combinations

		Material / Joining Techn.	Steel/Steel	Steel/ High tensile steel	Steel/ Aluminium	Aluminium/ Aluminium	High tensile steel/ Aluminium	High tensile Steel/ High tensile steel	Aluminium/ Steel-Sandwich	Steel/ Composites	Aluminium/ Composites	Steel/CFK	CFK/CFK
Warm Joining Techniques	1.	Spot welding	in serial production	in serial production	not possible	in serial production	not possible	in serial production	in development	in development	not possible	not possible	not possible
	2.	Spot weld-gluing	in serial production	in serial production	not possible	in development	not possible	in serial production	in development	in development	not possible	not possible	not possible
	3.	MIG welding	in serial production	in serial production	not possible	in serial production	not possible	in serial production	not possible	not possible	not possible	not possible	not possible
	4.	Tandem MIG welding	in serial production	in serial production	not possible	in serial production	not possible	in serial production	not possible	not possible	not possible	not possible	not possible
	5.	MAG welding	in serial production	in serial production	not possible	in serial production	not possible	in serial production	not possible	not possible	not possible	not possible	not possible
	6.	WIG welding	in serial production	technical bases are developed	not possible	in serial production	not possible	in serial production	not possible	not possible	not possible	not possible	not possible
	7.	Laser welding (CO_2)	in serial production	in serial production	in development	in serial production	in development	in serial production	not possible	not possible	not possible	not possible	not possible
	8.	Laser welding (Diodes)	in serial production	in serial production	in development	in serial production	in development	in serial production	not possible	not possible	not possible	not possible	not possible
	9.	Laser welding (YAG)	in serial production	in serial production	in development	in serial production	in development	in serial production	not possible	not possible	not possible	not possible	not possible
	10.	Projection welding	in serial production	in serial production	not possible	in development	not possible	in serial production	not possible	not possible	not possible	not possible	not possible
	11.	Laser brazing	in serial production	technical bases are developed	in serial production	in development	in serial production	technical bases are developed	not possible	not possible	not possible	not possible	not possible
	12.	MAG brazing	in serial production	in development	in development	not possible	in development	in development	not possible	not possible	not possible	not possible	not possible
Cold Joining Techniques	13.	Punch-riveting	in serial production	in development	in serial production	in serial production	in serial production	in development	technical bases are developed	technical bases are developed	technical bases are developed	in development	in development
	14.	Blind-riveting	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
	15.	Clinching	in serial production	in development	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development	in development
	16.	Flanging	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
Gluing	17.	Cohesiveness-gluing	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development

Legend: in serial production; technical bases are developed; in development; not possible

Table 4.3: Matrix of approved Joining Techniques and material combinations.

The development of this matrix is another step towards the development of a cost estimation methodology. It forms a basis of technical constraints for the joining selection process in the preliminary work phase of the automotive PDP.

4.6.3 Elaboration of Complexity Sheets with appendant Joining Side Coefficient

Diverse interviews with experts from BIW manufacturing made it clear that the technical complexity of new concepts plays an important rule in the BIW manufacturing process. During the interviews, the respondents gave detailed representations and documents concerning the various types of possible JT's together with their strengths and weaknesses. In point of fact, the relationship between JT's and suitable materials of the JS's was the subject of most of the interviews.

In the course of the research detailed analyses in the planning and manufacturing area of this important subject led to the development of complexity sheets by the researcher itemising the technical difficulties that appear when two metal sheets are to be joined together. These technical characteristics are associated with the shape and surface of the BIW sheets that are to be joined. A change in these characteristics has a significant impact on the cycle time of the BIW joining process. Furthermore an increase of cycle time will lead to an increase in manufacturing cost. To compensate for this cycle time variation a Joining Side Coefficient (JSC) had been established. This Joining Side Coefficient is derived from the complexity level of a Joining Side that is deduced from the complexity sheet. This sheet was elaborated by the researcher for every single Joining Technique in close collaboration with Planning and Manufacturing. Thereby reference was made to data and documents internal to the sponsoring company.

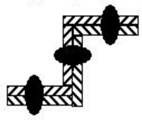
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Two-blank sheet-welding of equal blank sheet thickness 0,7 mm < blank sheet thickness > 1,5 mm, variation of blank sheet thickness 0%.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width after reference (BMW standard), 20 mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Great degree of freedom for the welding gun, little steel in "secondary welding gun window", easily positioning of the welding gun because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Two-blank sheet-welding of different blank sheet thickness 0,7 mm < blank sheet thickness > 1,5 mm, variation of blank sheet thickness maximum 20%.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of reference (BMW standard), effective joining width narrow, 20 mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Average volume of steel in the "secondary welding gun window", normal size of the welding gun (length of piole X < 800m), normal positioning of welding gun because of an appropriate blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Two or three-blank sheet-welding of equal blank sheet thickness 0,7 mm < blank sheet thickness > 1,5 mm, variation of blank sheet thickness > 20%.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 15mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised.	
	4. Accessibility:	Shortage of space , great amount of steel in the "secondary welding gun window", big welding gun (length of piole X > 800m), difficult positioning of welding gun because of a complicate blank sheet contour ⇒stepped part contour.	

Table 4.4: Complexity level with JS Coefficient for the spot welding technology.

In this sheet features of material properties are described and subdivided in four sections. The overall contents of the four sections were the complexities of the blank sheet contour with its material thickness, effective width of the joining cross section, the surface condition and the accessibility of the joining zone. The criteria listed extend the joining process, consequently the cycle time, and therewith the cost of manufacturing. To make this extension palpable a norm was introduced on the basis of the 100% standard cycle time. To compensate for deviations from this norm, a joining side coefficient (JSC) has been established. For every combination of JS's a JSC will be assigned depending on the complexity level of pertinent criteria, which may involve a) contour of the part, b) material thickness, c) effective width of the joining cross section, d) appropriate surface condition, and e) accessibility of the joining zone. A JS combination that satisfies the basic criteria of complexity level 1 is a standard joining process without variation and is given a standard cycle time setting the 100% basis. This complexity level is taken as the unit JSC=1,00. Table 4.4 shows that an increase in the difficulties listed, i.e., of the complexity level, can result in a JSC with a cycle time of up to 150% of the unit value.

The JSC is another important evaluation parameter within the development of a new BIW cost estimating methodology. For every single Joining Technique a particular Complexity Sheet with its derived JSC can be found in Appendix 6.

4.6.4 Elaboration of Joining Technique Cost Templates

The survey and classification of all BIW Joining Techniques with their attendant costs belong to the core of the BIW cost estimating methodology. It became apparent that a detailed and verified cost analysis for every JT can be realised only in close and extensive collaboration with experts from Planning, Finance and Manufacturing. On the basis of numerous profitable discussions with such experts the researcher developed a Joining Technique cost template for every approved BIW Joining Technique. This template contains data pertaining on the one hand to investment cost and on the other to manufacturing cost.

On the basis of an analysis of the standard BIW manufacturing process in the sponsoring company the standard parameters of a general automotive production cycle were ascertained. This analysis led to the result that a general vehicle model is produced for a period of 7 years, with 244 man days per year, 2 shifts per day and 465 minutes per shift. These boundary conditions served as a basis for a calculation of the investment cost per JT Working Content, which is the smallest unit of work. On the basis of these investment cost data and the technical data contained on the data sheet of every Joining Technique, e.g. spot welding, riveting, etc., it was possible to calculate the total number of Working Contents yielded in the life cycle of the joining equipment. For this purpose a standard example was taken. The case of two metal sheets with a Joining Side length of 1000mm was taken as a standard BIW joining object. With Computer animations the exact joining, robot and turntable times for the respective Joining Technique were simulated and collected. From this data collection the cycle time of a joining machine and therewith the total number of Working Contents yielded were calculated. Subsequently the total investment cost was divided by this total number of Working Contents. The result was the investment cost of one Working Content of the joining equipment under consideration.

Ascertaining the manufacturing cost of every single Joining Technique proved to be more complex and time consuming. These costs were subdivided into a) cost for manufacturing resources, b) cost for electricity, water, air and gas, and c) cost for maintenance. They were collected by evaluation and analysis of the data recorded in the BIW manufacturing plant for every joining machine. In addition the technical data sheets of the joining machines were evaluated and analysed. The cost data thus obtained were confirmed by experts from Planning, Finance and Manufacturing during the overall process of data collection. Finally the manufacturing cost for one Working Content of every Joining Technique and material combination was calculated. These costs were summarised in Joining Technique cost templates in compliance with the sponsoring company's regulations for publication, as shown in Table 4.5.

These new developed templates enable members of the design, planning and finance departments to estimate the total investment and manufacturing cost per operational unit for each separate JT. This means, for example, the cost for one spot-welding point.

The development of these templates, which can be found in appendix 7, is another important step towards the cost estimation of a BIW design concept. By means of former BIW design concepts, whose cost had already been calculated by Finance, first cost estimates were done by hand by utilisation of cost templates. These first cost estimations were successful and prove that the cost data identified in the Joining Technique cost templates are complete and accurate. To verify the results of the first cost estimates, interviews with experts from the finance and planning departments and additionally from the manufacturing area were conducted. The outcomes of these Expert interviews were very satisfactory.

Joining Technique:	**Resistance spot welding**		**Steel - Steel**	
Installation:	Flexible manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of spot welding.			
Investment cost:	**198.744 EURO**		**per spot:**	**0,00531 €/spot**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1412 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,20 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,0016	2.556,46 €	4,09 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**8,58 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**16,06 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	44 sec			
- Robot time:	2 sec			
- Turntable time:	5 sec		**per Working Content:**	
- Total cycle time:	51 sec	(1412 spots/hour)	**per spot:**	**0,01137 €/spot**

Table 4.5: Joining Technique cost template for resistance spot welding.

4.6.5 Definition of the Interrelationship between Joining Parts and Joining Sides

A last but not least examination for the development of the BIW cost estimating methodology was the analysis of the interrelationship between joining parts and Joining Sides. The question how the number of parts to be joined influences the average car body was studied in an analysis of internal company documents conducted with the support of the design department. A survey of the automotive BIW design concepts of the past ten years showed clearly that the number of such parts constantly increases. By analysing three different integral bodies of four automotive manufacturers in terms of the number of joining parts it became apparent that the range extends between 200 to 400 parts, depending on the vehicle class, as shown in Figure 4.2.

A comparison of the number of joining parts with that of WC's in Figure 4.2 shows that the two are unrelated. As illustrated in the diagram, the number of WC's ranges between 4500 and 9500. Around 90 % of these WC's, which are necessary to manufacture the car body, are based on JT. The remaining 10% of the WC's are due to handling and reworking procedures.

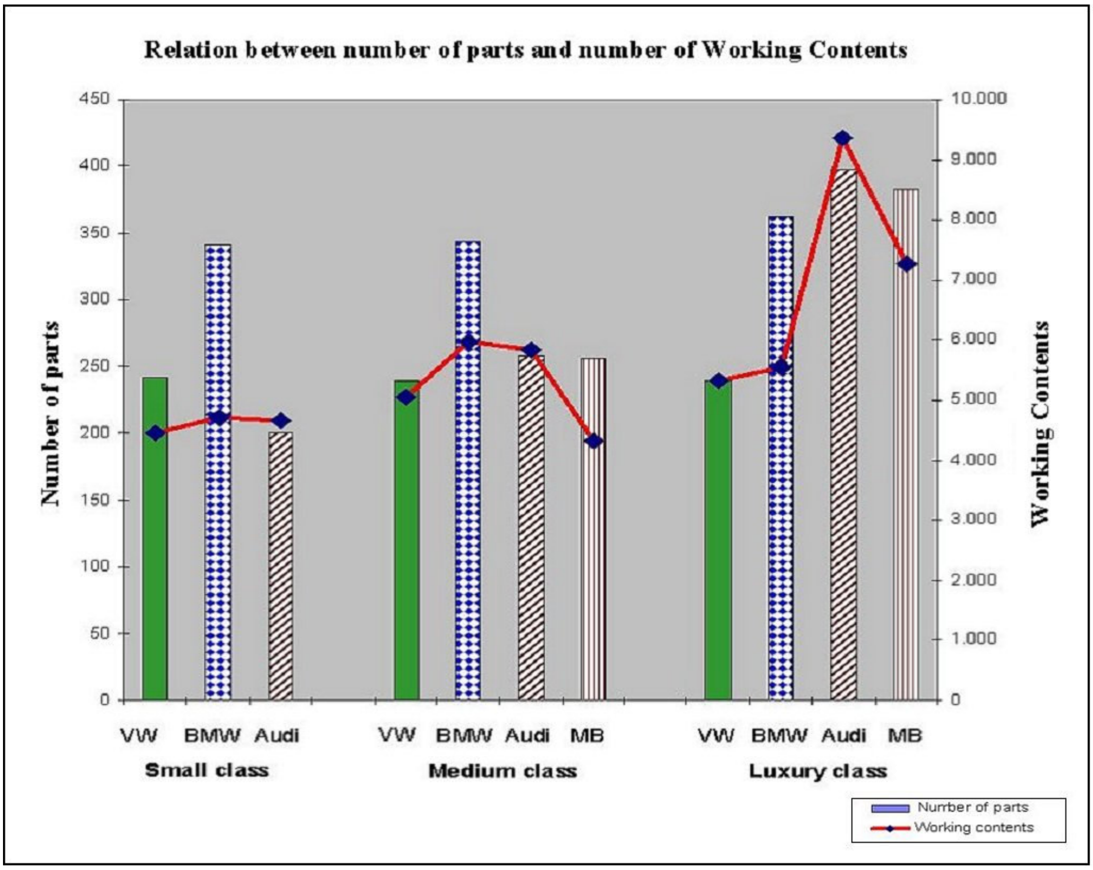


Figure 4.2: Relation between number of joining parts and Working Contents.

To give an impression of the sizable number of blank sheets used in the assembly of a car body, Figure 4.3 shows a typical car body front-end manufactured from the new composite aluminium-steel technology. This aluminium-steel composite front-end of a medium class vehicle shown in the below drawing is assembled from approximately 100 blank sheets.

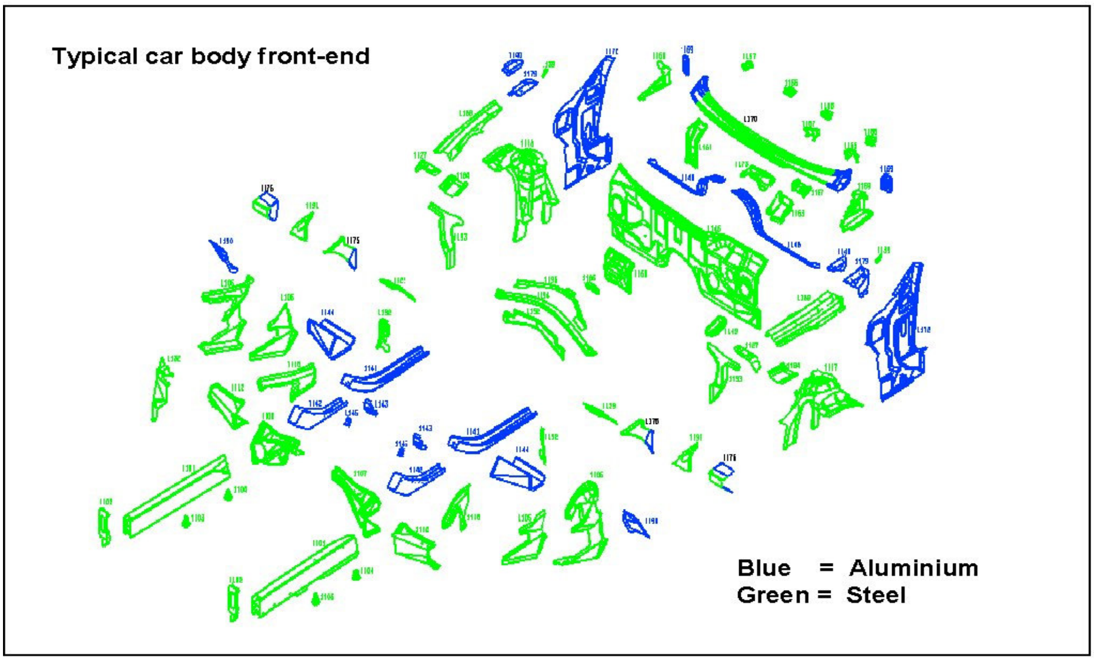


Figure 4.3: Aluminium-steel composite car body front-end.

On this basis, the conversion diagram of Figure 4.3 shows that over 2200 WC's are required for the joining operation of the car body front-end. According to this example, around 2000 single JT WC's must be used in the manufacturing process of the aluminium-steel composite front-end. These enormous numbers of JT WC's have been assigned by the designer.

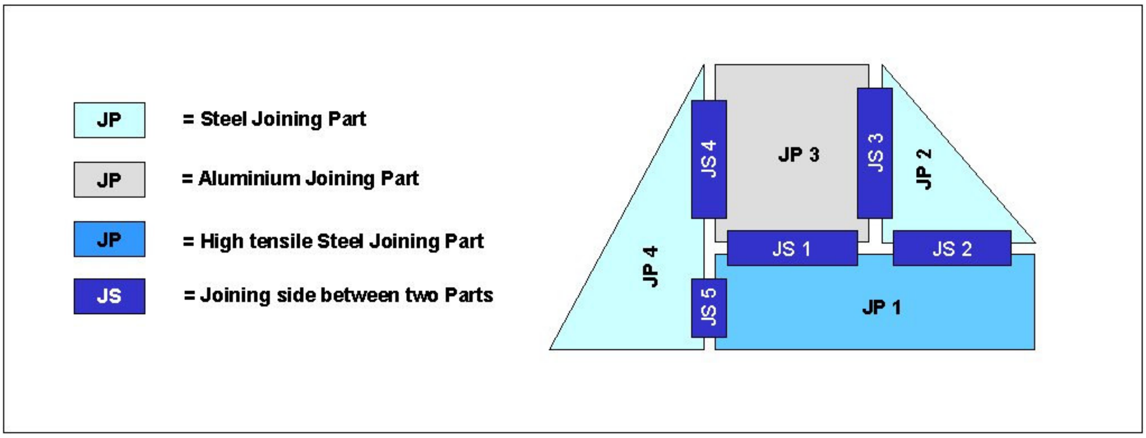


Figure 4.4: Interrelationship between Joining Parts and Joining Sides in a simplified model.

In Figure 4.4, a simplified model illustrates the connection between joining parts with their diversity of material and their appending Joining Sides (JS's). This example illustrates the complexity of the decision making process behind the allocation of material and JT. For every JS between two joining parts, at least one applicable JT must be selected on the basis of both technical and economic criteria. In consideration of the technical constraints of Table 4.3, a certain number of JT's are allocated for each JS.

Considering the oversimplified example shown in Figure 4.4 representing a spring carrier with 5 JS's and its material diversity, the possible number of JT combinations can be calculated.

$$\begin{aligned} NJTC &= \prod_{n=1}^{5} NJT_{JSn} \\ &= NJT_{JS1} * NJT_{JS2} * NJT_{JS3} * NJT_{JS4} * NJT_{JS5} \\ &= 6 * 12 * 6 * 6 * 12 \\ &= 31{,}104 \end{aligned}$$

$NJTC$: *Number of Joining technique combinations*

NJT_{JSn} : *Number of allocated Joining techniques at Joining side n*

In view of the number of authorised JT's for every JS, the possible number of JT combinations has been calculated as 31,104.

Even from this example, it is evident that in the worse case a designer has to verify 31,104 possible JT combinations. Under these circumstances it will be difficult to achieve the technical and economical optimum identified by exhaustive enumeration. To emphasise this conclusion further, it may be mentioned that in fact, in an automotive BIW front-end design, see Figure 4.3, the expectation is that there will be approximately 200 JS's, each with an average of six appropriate JT's. In this case the number of possible combinations is 6^{200}. This number of possible combination will increase if the entire body frame is considered.

To make this problem more evident the following diagram shows the connection between the number of JS's and the resulting number of possible JT combinations. Figure 4.5 shows the exponential increase in the number of possible JT combinations determined by the possible number of authorised JT's per JS. Every curve of the diagram represents a certain number of authorised JT's. It shows what will happen if the number of JS's of a BIW increases. For example the left-most curve, marked with eggshaped dots, represents the case in which 6 JT's per JS are authorised. It shows the possible number of JT combinations if 1, 2, 3, … 10 JS's of a BIW are to be joined together.

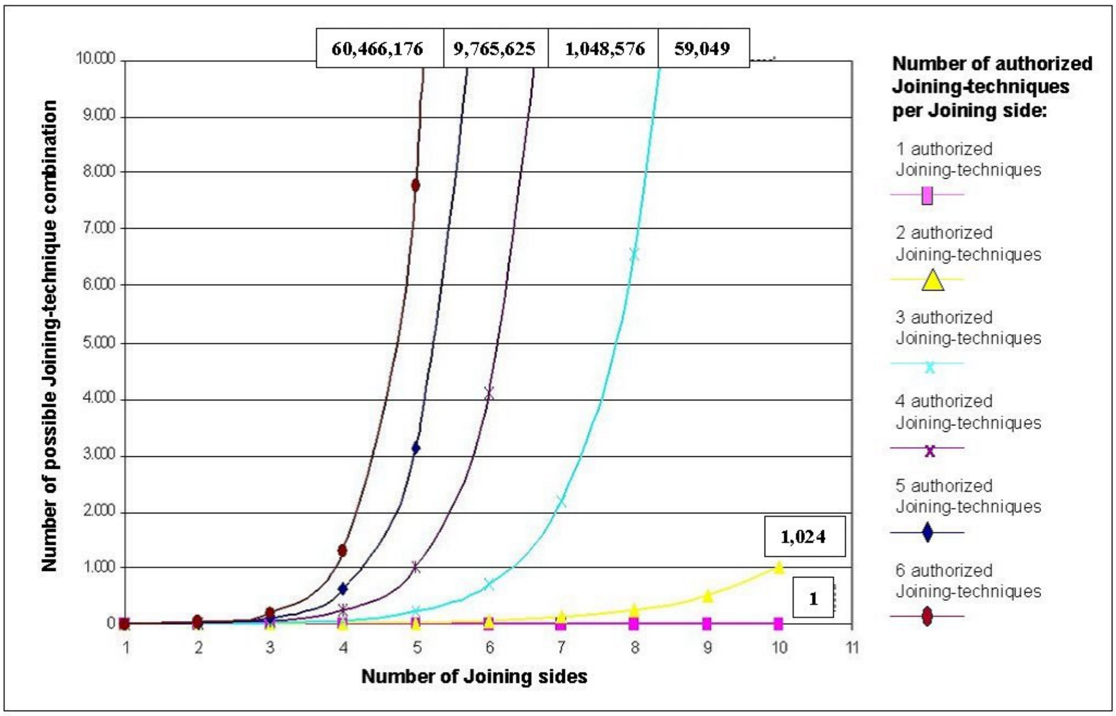


Figure 4.5: Dependency between number of possible Joining Technique combinations and the number of authorised Joining Techniques per Joining Side.

In the case of a car body component having 10 sides to be joined, each with 6 authorised JT's, the total number of possible JT combinations would be 6^{10} = 60,466,176, as shown in Figure 4.5. Finding a global optimum among such a great number of possible JT combinations requires an optimisation technique if the enumeration problem is to be avoided.

4.7 Summary

The Industrial Survey Chapter deals with data collection, findings and their elaboration into tables, matrices and sheets. For this purpose a questionnaire and interviews are utilised; in addition documents and literature internal to the sponsoring company were analysed.

The questionnaire revealed the lack and the need of a proper Body-in-white cost estimation method within the Preliminary Work Phase of the automotive Product

Development Process. The interviews emphasised these findings and confirmed the research hypothesis that it is possible to develop a cost estimating method on the basis of information contained in the specification data of BIW design concepts. It became apparent that Joining Techniques, which account for the major portion of BIW manufacturing costs, can be expressed as integral numbers of Working Contents. This opens the possibility of using Working Contents as a point of reference common to Design, Planning and Finance. In this wise, Working Contents become the basis for a BIW cost estimation methodology in connection with Joining Techniques.

In addition the interviews showed that no reliable information pertaining to the cost of Joining Techniques was available to make an early cost estimate of BIW design concepts feasible.

In the parallel process of analysing internal documents and literature, pertinent data and information was analysed and filtered. In the subsequent elaboration, data relevant to the development of the overall BIW manufacturing cost estimating methodology were concentrated into tailored tables, a matrix and templates. First a mathematical definition of BIW Working Contents was generated. Subsequently the technical interrelationship between joining materials and Joining Techniques was analysed and resumed in a matrix. This matrix provides the option of selecting the approved Joining Technique with its material combinations on the basis of technical considerations.

In like wise a scrutiny of BIW manufacturing process revealed a technically determined variation of the cycle time of the BIW joining process. Hence Complexity Sheets were elaborated that make these variations visible. To compensate for the variations a Joining Side Coefficient was developed.

The concluding analysis of BIW manufacturing cost led to the elaboration of Joining Cost Templates on the basis of Joining Technique investment and manufacturing cost. These templates constitute a core part of the cost estimating methodology aimed at.

Finally the interrelationship between joining parts and Joining Sides was illustrated by a simplified model, which was used to show the problem of Joining Technique selection. In this connection it was noted that the astonishing number of possible JT combinations for each JS in the Body-in-White design process requires application of an optimisation technique if the enumeration problem is to be avoided.

5 Development of a Cost Estimating Methodology

5.1 Introduction

Once the Industrial Survey has been applied and fundamental sheets, templates, matrices and tables have been elaborated, it is possible to start with the development of the cost estimation model. This model is aimed at providing Design with the option of selecting the most cost efficient Joining Technique combination and thereby analysing the relative manufacturing cost of new design concepts and at assisting with cost reduction in the Preliminary Work Phase of the Product Development Process. In the beginning of the cost model development process, a basic modelling process is being presented. Subsequently the Joining Technique Selection Problem is formulated as a model and a corresponding algorithm is developed. This algorithm serves as a foundation upon which to select an appropriate optimisation procedure for optimal Joining Technology selection in terms of manufacturing cost. An investigation of current assignment optimisation methods be associated with the Joining Technique selection process is carried out to find appropriate optimisation problems which can solve the Joining Technique Selection Problem. The analysis and applications of optimisation methods from the area of Operations Research provides first appropriate results. Finally the overall cost estimating model is elaborated by integrating the optimisation method with all pertinent data.

5.2 Methodology Developing Process

5.2.1 Cost Modelling Process

Cost Modelling involves the construction of mathematical models, also known as CER's (Cost Estimating Relationships) and TER's (Time Estimating Relationships) to describe project, process or product costs [Ogunlana, 1989]. According to Osterwald [1992], the objective of the Cost Modelling Process is the identification and collection of product, process and cost information which are analysed in order to estimate cost or time on the basis of technical parameters that work as cost drivers.

Wang [2000] state that companies which have to resist against competition on today's market have to improve their business operations and identify their core competencies by addressing the following emerging market requirements:

- Increasing emphasis on minimising overall product cost.
- Greater choice of available manufacturing processes and materials.
- Increasing demand for breakthrough technologies.
- Shorter product development cycle times.

These requirements are requested in the present research project. Wang and Stockton [2000] state that they are affecting the market environment and have significant effects on the cost estimating process and similar consequences on the cost model development process. Rush and Roy [2001] add that as a result of this, an increasing number of cost models will be required to effectively deal with a greater level of product and process complexity, and to respond to a greater choice of process and materials available. Likewise the increasing emphasis on minimising the overall product life cycle costs and production cycle times plays an increasing role [Stockton *et al.*, 2000]. This will result in a greater need for more efficient and formalised data identification and collection. Stockton *et al.* [2001] confirm that this will be especially critical for cost models developed at the early stages of the product development process, when the availability of historical data is limited. Wang [2000] add that the lack of costing data and the limited availability of process and product expertise at the concept stage of a new product, will significantly affect the tasks of data collection and data identification; hence the time, cost and accuracy of cost modelling process, and the cost model itself will also be affected.

Pursuant to Stockton *et al.* [1998], a traditional Cost Modelling Process approach, which is still in use today, is basically based on the sequence of data collection, data identification, data analysis and decision making tasks as illustrated in Figure 5.1. According to Arvelo and Stockton [2007], the Cost Modelling process essentially consists of a series of stages or data identification tasks whose main function is to identify the potential cost drivers or predictor variables for the generation of CER's. The data identification tasks are then followed by the collection of relevant data for these cost drivers, i.e data collection tasks. The final stage of the process, the data analysis task, involves the selection of the most appropriate data analysis method and the analysis of the collected data to identify the relationships between the resources which the models is required for material, labour, process time, tooling, manning levels and its cost drivers.

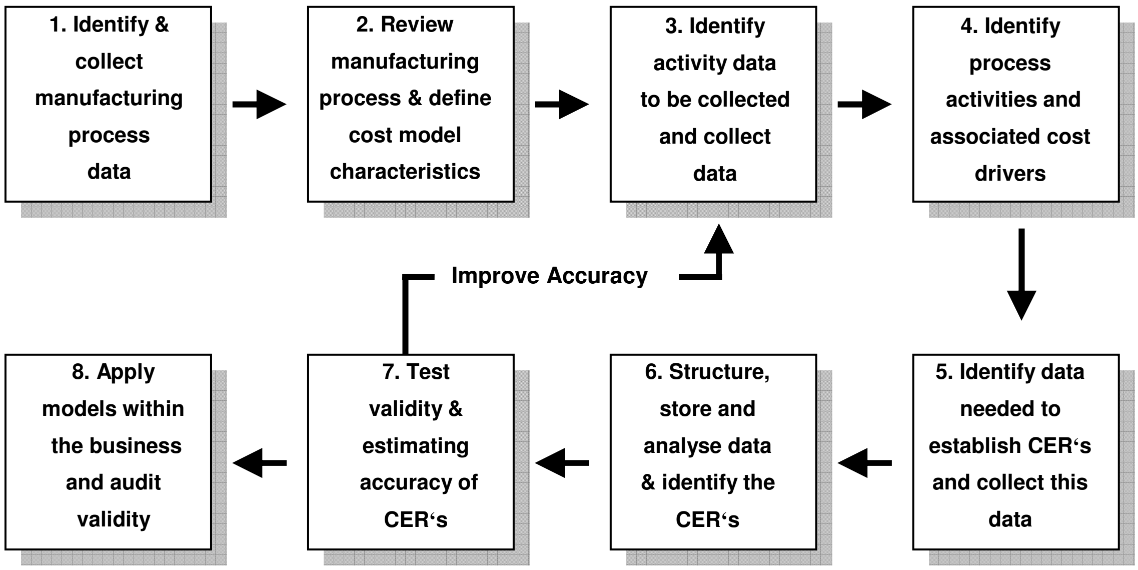


Figure 5.1: The Cost Modelling Process [Bush, 1994].

The previous statements show the close connection between today's cost estimating and cost modelling. Likewise it becomes apparent that the need of historical data is a prevailing problem for cost modelling. This primary and time consuming task of collecting and evaluating cost and technical data was accomplished in the previous Chapter 4, explicitly in section 4.6.2 to section 4.6.4. Steps of the cost modelling process of Bush [1994] in Figure 5.1 are then carried out in part. Likewise the interrelationship between joining parts and Joining Sides is discussed in section 4.6.5. This relationship is fundamental for the ensuing development of the algorithm for a Joining Technique Selection based on manufacturing cost. The elaboration of this algorithm is a preliminary step for the subsequent process of seeking and finding an optimisation method (optimisation problem) appropriate for finding the most cost efficient Joining Technique combination in terms of manufacturing costs, see sections 5.4. to section 5.6. Finally the overall cost estimation model is elaborated by integrating the optimisation method with all pertinent data as presented in section 5.8.

5.2.2 The aim of the cost estimating model

The aim of the research project is to find a model that allows the ranking of competing BIW design concepts in terms of manufacturing cost. In this regard the selection of cost effective Joining Techniques (joining processes) is central. What is sought is a relative cost, not an absolute one. But the model must also meet certain over-riding constraints, of which the principal ones are these:

- that it admit of application to BIW design concepts with different materials, allowing comparison between competing designs.
- that it admit of early use in the BIW Product development process (since its purpose is to guide design decisions)
- that it admit of application by BIW engineers

The result of the cost estimating methodology must be seen as a set of broad indicators to guide decision-making, not as precise predictions. With this in mind the problem is approached in the following way.

5.2.3 The Joining Technique Selection Problem formulated as a Model

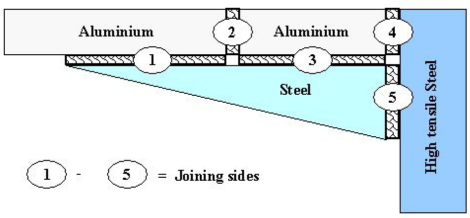
When developing a model, one may well begin with a verbal description of the problem, together with its objectives and constraints, and then move forward in formulating first a simple mathematical model. The following section will describe the procedure of the Joining Technique Selection Problem (JTSP) and derive an algorithm.
Decision-making is a key managerial responsibility within the design process. The process is initiated whenever a designer observes a problem. Perhaps unconsciously, the designer first defines the problem and then formulates the objective of a design concept, recognises the constraints, and evaluates the alternative. After that, the BIW decision maker selects the apparently “best” course of action – the one that will lead to the optimum solution. According to Levin and Kirkpatrick [1982], this process of analysis, whether formal or informal, takes two basic forms:
Qualitative and *quantitative*. Using only a qualitative approach, a designer would rely on personal judgement or past experience with similar problems. Such an intuitive “feel” for the situation may be sufficient for making a decision.

Yet designers may require quantitative analyses. This would occur when they have no experience with similar problems. Or it would occur when a problem is so important and complex that it requires a thorough analysis if a great deal of money or a perplexing set of variables is involved. Or the problem may be repetitive and simple, and a qualitative procedure can save the designer's time.

The BIW designer, who is the decision maker within the JT Selection process, is expected to have the expertise to select the optimal JT's for every JS of a new design concept in terms of technical aspects like stiffness, corrosion, reliability etc.

In contrast, the BIW designer is not at home in cost decision methodologies and the corresponding optimisation procedures. The designer has to make a decision regarding the optimal combination of JT's in respect of the manufacturing cost incurred. These manufacturing costs include the cost rates for the fixed investment and the operational cost for the JT's with its machinery that are recorded in "Joining Technique cost templates" added to the Appendix 7.

Once the new design concept is completed, the JT Selection process starts with the identification of the Joining Sides (JS's) within the new design concept. Therefore the combination of the material and the length of the JS's of participating parts is analysed, its components being listed in a table, as shown in Figure 5.2.



	Material	Length [mm]
1. Joining side	Aluminium - Steel	520
2. Joining side	Aluminium - Aluminium	275
3. Joining side	Aluminium - Steel	460
4. Joining side	Alu. - High tensile Steel	275
5. Joining side	Steel - High tensile Steel	350

Figure 5.2: Simplified schematic of an automotive wheelhouse with joining parts, sides and lengths.

Hence, a certain "identity number" is attached to every JS. The BIW designer who is in charge of the design drawings could automatically do this data-transfer with only slight time expenditure. This allocation of technical data to every JS is an important data input for the JTSM. Via the combination of the JS's materials, the "authorised" JT's could be defined precisely, as indicated in section 4.6.2. The length of the JS is an indicator for the manufacturing cost. The already analysed and summarised manufacturing cost for every single JT within the JT cost templates is linearly dependent on the JS length.

5.2.4 Algorithm for the Joining Technique Selection Process

As the BIW designer is responsible for assigning the optimal JT to all JS's of the new design concept, the designer must conduct a separate process for every JS.
As a first step towards the development of an algorithm for the assigning the optimal JT to every JS, a simplified model of the JT Selection process is illustrated in Figure 5.3.

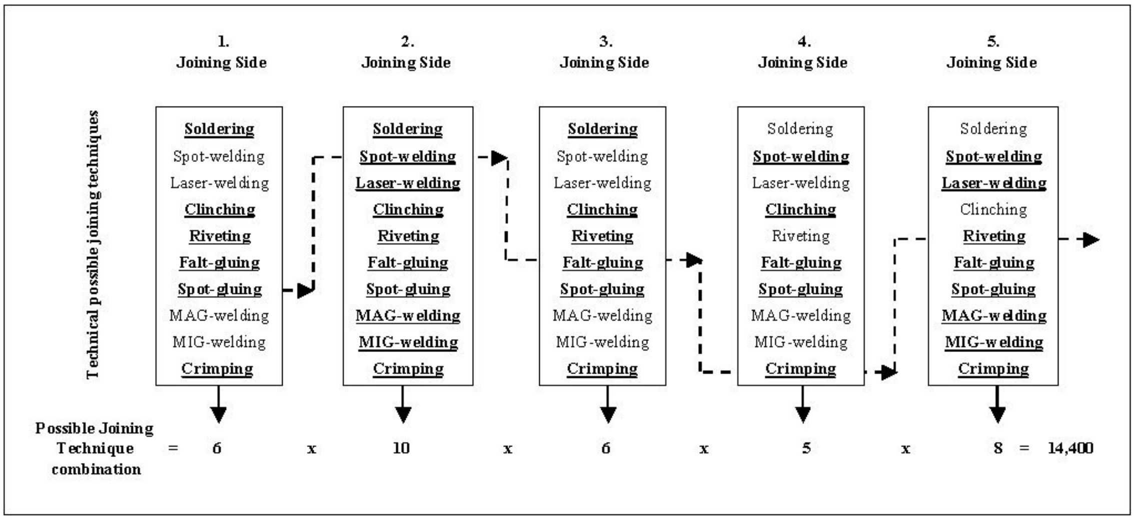


Figure 5.3: Allocation of Joining Techniques to the Joining Sides.

This model lists in columns all possible JT's for every single JS. Within these columns all applicable JT's, also called "authorised" JT's, are underlined.
At this point, the objective of the method is the search for the optimal combination of authorised JT's in terms of manufacturing cost. In the illustration above, the line of arrows shows only one possible combination of assigning JT's to the JS's out of the 14,400 possible combinations.
A further stage for the development of the cost estimation methodology consists in connecting the technical data of JT's and JS's with associated costs. Similarly the objective of this stage is to bundle the essential technical and financial data of a BIW design concept into a central matrix as depicted in Table 5.1:. This JT-JS matrix is a further development of Figure 5.3 in this way that the joining cost c_{mn} arising from each single joining process is assigned to each JS listed. Additionally the JS's are given in

terms of length and material because these are required for determining the number of WC's. The JT's necessary for the joining process at each JS are listed in rows. They are also assigned the joining costs arising from each single joining process.

Joining side No.:		1.	2.	3.	...	n
Joining side Length [mm]		Len JS 1	Len JS 2	Len JS 3	...	Len JS n
Joining side Material		Mat JS 1	Mat JS 2	Mat JS 3	...	Mat JS n
No.	Joining Technique / Cost	Cost JS1	Cost JS2	Cost JS3	...	Cost JSn
1.	JT1	c_{11}	c_{12}	c_{13}	..	c_{1n}
2.	JT2	c_{21}	c_{22}	c_{23}	...	c_{2n}
3.	JT2	c_{31}	c_{32}	c_{33}	...	c_{3n}
...	...	...	...	...	...	...
m	JTm	c_{m1}	c_{m2}	c_{m3}	...	c_{mn}

JT = Joining technique; JS = Joining side; Len = Length; Mat = Material; c_{mn} = cost of Joining technique m at Joining side n

Table 5.1: Joining Technique - Joining Side Matrix.

At this stage the transfer of the previous model and the JT-JS matrix into a simplified algorithm could be elaborated without substantial effort. This simplified algorithm of the JT Selection process can be described in a procedure with certain sequences of steps.

The procedure begins with the analysis of the total number n of JS's. Afterwards the procedure starts the first loop with an analysis of the authorised JT's for the first JS j =1. Out of these authorised JT's the optimal JT (in terms of cost) will be assigned to JS j=1. In a next stage of the procedure the actual number of the JS j =1 is compared to the total number n of JS's. If the number of the JS is smaller than the total number of JS's, the algorithm will jump back to the beginning of the procedure and carry out the same process with the second JS j =2.

The procedure will be finished, if the actual number of the JS is equal to the total number of JS's (j = n). At the end the optimal JT combination will be displayed and the optimal minimum cost of all optimal JT's of JS j = 1, 2, 3, …, n will be summed up.

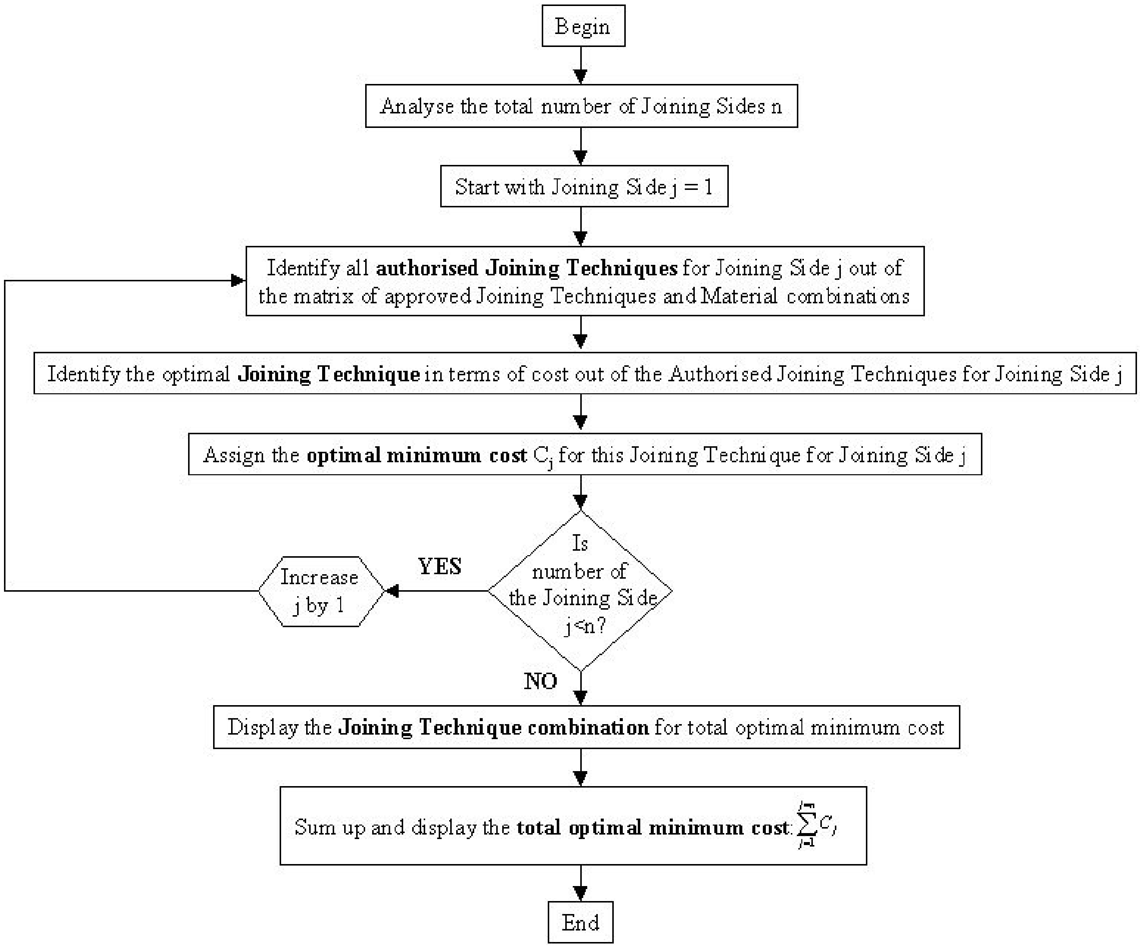


Figure 5.4: Algorithm for optimal Joining Technique Selection in terms of costs.

This iterative procedure, illustrated in Figure 5.4, describes a first basic approach for an optimisation algorithm that appraises the optimal JT combination in terms of costs.
The transformation of the emblematised simplified model and the JT-JS matrix into an algorithm for optimal Joining Technique Selection in terms of minimum costs is an intermediate stage for the development process of a cost estimation methodology. Likewise this systematic compilation of essentials into a matrix is the foundation for the analysis of already existent and elaborate optimisation problems that could be implicated with the Joining Technique Selection Problem.

5.3 Applicable Optimisation Methods

The algorithm for selection of the optimal Joining Technique makes it clear that the optimisation problem arises in the area of allocation or assignment problems.

The assignment problem is one of the fundamental combinatorial optimisation problems in the branch of optimisation or operations research in mathematics. It consists of finding a maximum weight matching in a weighted bipartite graph [Wikipedia, 2008]. In its most general form, the problem is as follows:

There are a number of agents and a number of tasks. Any agent can be assigned to perform any task, incurring some cost that may vary depending on the agent-task assignment. It is required to perform all tasks by assigning exactly one agent to each task in such a way that the total cost of the assignment is minimized. If the number of agents is equal that of the tasks, and if the total cost of the assignment for all tasks is equal to the sum of the costs for each agent (or the sum of the costs for each task, which is the same thing in this case), then the problem is called the *Linear assignment problem*. Commonly, when the *Assignment problem* is mentioned without any additional qualification, the *Linear assignment problem* is meant.

According to Hillier and Lieberman [1988], an assignment problem is defined by the following conditions:

1.) There is a set of jobs (of any type) to be done.
2.) Enough resources are available for doing all of them.
3.) At least some of the jobs can be done in different ways and hence by using different amounts and combination of resources.
4.) Some of the ways of doing these jobs are better than others (e.g. are less costly or more profitable).

Therefore, the problem is to allocate the resources to the jobs in such a way that overall efficiency is maximised; for example, so that total cost is minimised or total profit is maximised. In the simplest allocation problem of this type each job requires one and only one resource, and there are the same number of jobs and resources. This problem is called the *assignment problem* because it involves assigning one resource to each job [Zimmermann, 1986]. The resource may very well be a Joining Technique. There is a cost or profit associated with each combination of job and resource. The problem is to assign the resources so that the total cost of doing the jobs is minimised or the total profit is maximised. This type of problem becomes more complex if some of the jobs

require more than one resource and if the resource can be used for more than one job. Then the problem involves dividing the resources and jobs appropriately.
The assignment problem is a special case of the transportation problem, which is a special case of the minimum cost flow problem, which in turn is a special case of a linear programming out of Operational Research [Wikipedia, 2008].
In the following a survey of already available assignment optimisation methods in the area of Operational Research stresses which kind of mathematical solution techniques are available to the Joining Technique selection problem.

5.4 Operational Research

Operations Research (OR) in the US, and Operational Research in the UK, is an interdisciplinary branch of applied mathematics which uses methods like mathematical modeling, statistics, and algorithms to arrive at optimal or good decisions in complex problems which are concerned with optimising the maxima (profit, faster assembly line, greater crop yield, higher bandwidth, etc) or minima (lesser cost, lowered risk, etc.) of some objective function [Winston, 2003]. The eventual intention behind using operations research is to elicit mathematically a best possible solution to a problem, i.e. a solution that improves or optimizes the performance of the system.
According to Thierauf [1978], in recent years, operational researchers have been showing managers how to avoid some of the perplexity that relates to decision-making. They have developed various mathematical or OR techniques for evaluating possible courses of action. Some of these techniques are best suited to situations in which all the factors are known or predictable, but the complexity is so great that the human mind cannot arrive at a wholly rational decision.
Whatever the orientation of these OR techniques, their central focus is to improve the quality of the decision maker’s final decision.

5.4.1 Operational Research Models and Problems

This section is a short introduction to OR models and problems that are useful in analysing decision problems. The emphasis will be on the potential practical applications of these “tools”, rather than on their mathematical features.

A model that may be used to show the effects of a policy is called a *descriptive* or *what if?* model, because it is used as a test-bed to answer the question "What would happened (in the real system) if we did this?". This means that the responsibility for formulation policies still rests with the manager or analyst, and that the model itself gives no verdict on whether the results that emerge are "good" or "bad".

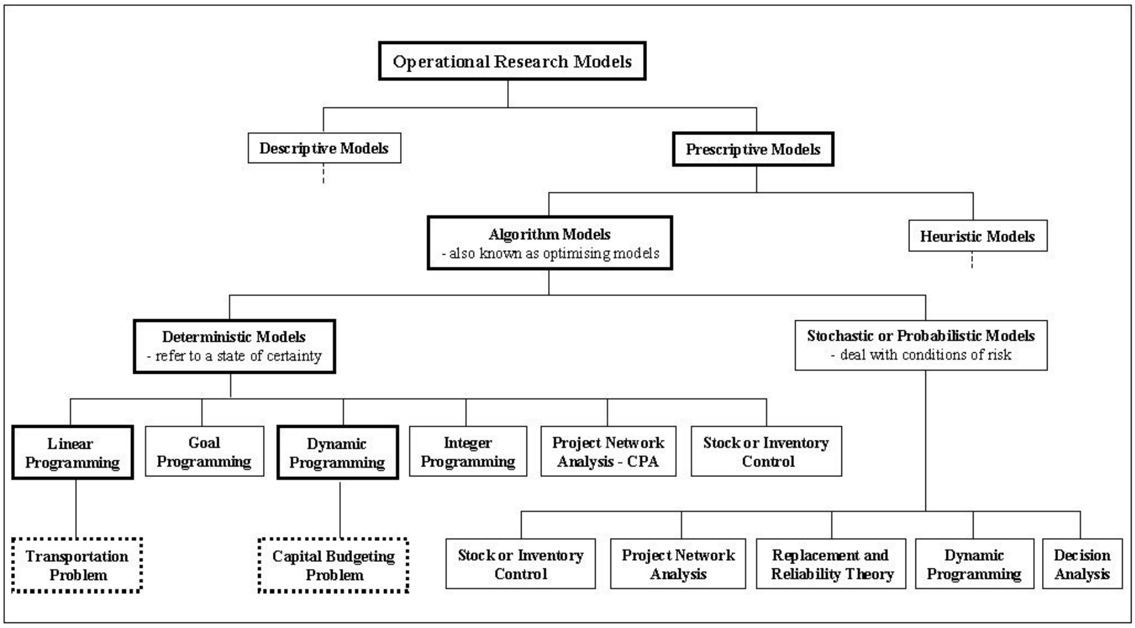


Figure 5.5: Structure of Operational Research models and problems.

The alternative approach, in which the model itself actually selects a policy, is called a *prescriptive* model. It is, however, very important to remember that the model only selects policies within limits set out by the manager and/or analyst, and that it uses the manager's criterion of what is 'best'. Prescriptive models come in two types:
algorithms (also known as optimising models) and *heuristics*. An algorithm is a procedure which, given a model and a criterion or criteria of what constitutes a "good" policy, will find the optimal (best) policy.
A heuristics model also selects policies in accordance with specified criteria, but the difference between it and algorithms is that the policy selected is not guaranteed to be the best one. Any "rule of thumb" is thus a heuristic, yet clearly a worthwhile heuristic must produce *good* solutions.
Whichever model is used, there is no absolute "right answer" as to how much detail should be included in it. Edwards [1985] states that there has to be a compromise

between accuracy, ease of comprehension and computational effort, and only those involved with a particular problem can decide how that compromise should be made. In simple terms, a model that helps to make a better decision is good enough.

For most purposes, there is no need for special terms to describe the level of detail of a model, but the distinction between *stochastic* and *deterministic* models is of crucial importance. Based on a state of certainty, the parameters of a deterministic model have no variability, each taking a single value. The number of wheels that a car has is a deterministic parameter, i.e. four: anything with more or fewer wheels is not a car. Stochastic models deal with conditions of *risk*, where some or all models' parameters take a range of values, it being necessary to allow for variabilities rather than simply deal with average or typical values.

Of the OR models presented, those best suited to the present research problem, which concerns methodology, are the prescriptive models, which actually select a policy, and of these the algorithmic ones (optimisation model), which, offering mathematical proof that they will always work for a certain range of cases, are guaranteed to yield the best solution in that range.

In a next stage the problem of JT Selection refers to a state of certainty, in which, there being no variability in the model's parameters, each takes a single value.

This is reason why the research problem belongs to the category of deterministic, algorithmic models. The algorithms to be dealt with first, all closely related, come under the heading of mathematical programming.

Within the deterministic category, this includes Linear Programming, the assignment and transportation algorithms and Dynamic Programming.

On the basis of OR problems and models investigated, the range of potential practical problems and models has been reduced. The sections that follow proceed on the assumption that the problem of optimising the process of JT selection is transferable to an assignment problem that belongs to the area of Linear Programming or Dynamic Programming.

5.5 Linear Programming adopted to the Joining Technique Selection Problem

Many people rank the development of LP among the most important scientific advances of the mid-twentieth century. Its impact since just 1950 has been extraordinary. Today it is a standard tool that has saved many thousands or millions of Euros for most companies or businesses of even moderate size in the various industrialised countries of the world.

5.5.1 The Nature of Linear Programming

Briefly, the most common type of application involves the general problem of allocating *limited resources* among *competing activities* in the best possible (i.e., optimal) way. The problem of allocation arises whenever the level of certain activities competing for required resources of limited availability must be selected. The variety of situations to which this description applies is diverse indeed, ranging from the allocation to products of production facilities to that of national resources to domestic needs, from portfolio selection to shipping patterns, from agricultural planning to the design of radiation therapy, and so on. The one ingredient common to each of these situations is the necessity for allocating resources to activities.

Although allocating resources to activities is the most common type of application, LP has numerous other important applications as well. In fact, any problem whose mathematical model fits the very general format for the LP model is an LP problem. Furthermore, a remarkably efficient solution procedure, call the *simplex method*, is available for solving LP problems of even enormous size. These are some of the reasons for the tremendous impact of LP in recent decades [Hillier and Lieberman, 1988]. Smythe and Johnson [1966] add, that LP, briefly described, deals with the optimisation of linear functions subject to linear constraints. The basic tool for solving such optimisation problems is an iterative process known as the *simplex algorithm*.

Hadley [1970] states that often an LP problem can be considered to be one concerned with the allocation of scarce resources – men, machines, and raw materials – to the manufacture of one or more products in such a way that the products meet certain specifications, while at the same time some objective function such as profit or cost is minimised or maximised.

As already mentioned in the previous sections, the *TP* is a particular type of the assignment problems of LP. The following section deals with the transfer and application of the JTSP to the TP.

5.5.2 The Transportation Problem applied to the Joining Technique Selection Problem

As the name suggests, the transportation problem was first formulated as a special procedure for finding the minimum cost program for distributing homogeneous units of a product from several points of supply (sources) to a number of points of demand (destinations). For example, a manufacturer may have 5 warehouses (sources) and 20 supermarkets (destinations), all located at different geographical points. For a specified time period, each source has a given capacity and each destination has a given requirement. Given the costs of transporting the product from each source to each destination, the objective is to schedule transportations from source to destination in such a way as to minimise the total transportation cost [Levin and Kirkpatrick, 1982].

Comparing the above-described example with our "Joining Technique Selection Problem" the source would be a warehouse with a variety of JT's (WC's) and the destination would be the right JS where the JT's (WC's) will be required. The different costs for transportation are similar to the different manufacturing costs for the JT's (WC's) at a certain JS. The objective of this LP problem is to optimise the JT Selection in such a way as to minimise the total cost of manufacturing.

In the following the general model for the TP will be described and applied to the JTSP. In particular, the general TP is concerned with the distribution of any commodity from any group of supply centres, called sources (JT's), to any group of receiving centres, called destinations (JS's), in such a way as to minimise the total distribution cost (manufacturing cost).

Thus, in general, source i (JT's) (i =1,2,…, m) has a supply of s_i units (JT's) to distribute to the destination j (JS) (j =1,2,3…, n), which has a demand for d_j units (WC's) to be received from the sources.

A basic assumption is that the cost of distributing units from source i to destination j is directly proportional to the number distributed, where c_{ij} (manufacturing cost) denotes the cost per unit distributed.

Letting the objective function Z be the total distribution cost (manufacturing cost) and x_{ij} (i =1,2, …, m; j =1,2, …, n) be the number of units (WC's) to be distributed from source i (Joining Technologies) to destination j (JS's), the LP formulation of this problem becomes:

Minimise $$Z := \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \qquad (5.1)$$

so that $$\sum_{j=1}^{n} x_{ij} = s_i, \quad \text{for } i = 1,2, \dots, m \qquad (5.2)$$

$$\sum_{i=1}^{m} x_{ij} = d_j, \quad \text{for } j = 1,2, \dots, n \qquad (5.3)$$

and $x_{ij} \geq 0$, for all i and j.

Any LP problem that fits this special formulation is of the TP type, regardless of its physical context.

A necessary and sufficient condition for a TP to have any feasible solutions is that

$$\sum_{i=1}^{m} s_i = \sum_{j=1}^{n} d_j \qquad (5.4)$$

This property may be verified by observing that the constraints require that

$$\sum_{i=1}^{m} s_i = \sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij} = \sum_{j=1}^{n}\sum_{i=1}^{m} x_{ij} = \sum_{j=1}^{n} d_j \qquad (5.5)$$

This information is appropriately stated as a *matrix* (i.e. a rectangular array) of numbers together with rim conditions. The combination of a matrix and rim conditions will also be called a *tableau*. Constructing a series of such tableaux can make all of the calculations necessary to solve the problem. The tableau of an m x n TP is illustrated in Table 5.2.

A condition in which total supply is equal to total demand is called *balanced*, a condition not likely to arise in actual practice. Most real problems are of the so-called *unbalanced* type, where supply and demand are unequal. If this is the case, a *fictitious* "source" or "destination", called the *dummy source* or *dummy destination*, can be introduced to take up the slack in order to convert the inequalities into equalities and satisfy the feasibility conditions. The JTSP will always be of the "*demand less than supply*" type.

Source i - Joining Techniques -	**Destination j** - Joining Sides - 1	2	…	n	**Supply** s_i
1	c_{11}	c_{12}	…	c_{1n}	s_1
2	c_{21}	c_{22}	…	c_{2n}	s_2
…	…	…	…	…	…
m	c_{m1}	c_{m2}	…	c_{mn}	s_m
Demand d_j	d_1	d_2	…	d_n	$\sum_{j=1}^{n+1} d_j$ \ $\sum_{i=1}^{m} s_i$

Table 5.2: Standard format of cost and requirements Tableau for the TP.

The demand d_j of the number of WC's is a function of the JS length, since every single WC of no matter which JT joins 50 mm of JS. For a JS with a length of 500mm the total demand d of WC's is computed as follows.

$$\text{Number of WC's} = \frac{\text{Joining Side length [mm]}}{\text{length per Working Content [mm]}} = \frac{\text{Len}_{JS}\ \text{[mm]}}{\text{Len}_{WC}\ \text{[mm]}} = \frac{500\ \text{mm}}{50\ \text{mm}} = \underline{\underline{10\ \text{WC's}}}$$

Following studies are conducted with integral numbers without loss of generality.

Transferring the TP to the JTSP of the research work delivers the transportation table illustrated in Table 5.3.

C

To / From	1. Joining Side	2. Joining Side	…	n. Joining Side	Fictitious n+1. Joining Side	J. Technique Supply s_i
1. Joining Technique						$s_1 = \frac{Len_{total}}{Len_{WC}}$
2. Joining Technique						…
A ← …			E			… → B
m. Joining Technique						$s_m = \frac{Len_{total}}{Len_{WC}}$
Joining Side Demand d_j	$d_1 = \frac{Len_{JS1}}{Len_{WC}}$	…	…	$d_n = \frac{Len_{JSn}}{Len_{WC}}$	$d_{n+1} := \sum_{i=1}^{m} s_i - \sum_{j=1}^{n} d_j$	$\sum_{j=1}^{n+1} d_j$ / $\sum_{i=1}^{m} s_i$

D

Table 5.3: Transportation table transformed to the JTSP.

The standard format for the transportation table has been divided into five lettered sections - A, B, C, D, and E – each of which will be explained in detail.

Section A: In this part the JT's (sources of supply) are listed, JT 1,2, …, *m*. Each row represents a JT (a number of WC's) that could be applied to the JS's. Combinations of JT's, for example welding and gluing, will be treated as single JT's.

Section B: In this column the number of necessary WC's are gathered to provide the JS with any JT sufficient to the task. For that purpose the supply of each JT has to be

$$s_i = \frac{\text{Len}_{\text{total}}}{\text{Len}_{\text{WC}}} \qquad \text{for all i = 1, …, m.} \qquad (5.6)$$

Section C: In this section the JS's (the destination points) are listed, JS's 1,2, …, *n*. Listed in addition is the fictitious n+1st JS responsible for the balance condition, in which total supply is equal to total demand. Each JS represents a column in the table. Because of the JS's length and the possible material combinations each JS has its own characteristic.

Section D: This lower section indicates the number of WC's (d_j) demanded by the JS given.

$$d_j = \frac{\text{Len}_{\text{JS}_j}}{\text{Len}_{\text{WC}}} \qquad \text{for j = 1, 2, …, n.} \tag{5.7}$$

The fictitious demand of the fictitious (dummy) JS is calculated from the difference:

$$\begin{aligned} d_{n+1} &= \sum_{i=1}^{m} s_i - \sum_{j=1}^{n} d_j = m \cdot \frac{\text{Len}_{\text{total}}}{\text{Len}_{\text{WC}}} - \sum_{j=1}^{n} \frac{\text{Len}_{\text{JS}_j}}{\text{Len}_{\text{WC}}} \\ &= m \cdot \frac{\text{Len}_{\text{total}}}{\text{Len}_{\text{WC}}} - \frac{\text{Len}_{\text{total}}}{\text{Len}_{\text{WC}}} = (m-1) \cdot \frac{\text{Len}_{\text{total}}}{\text{Len}_{\text{WC}}} \end{aligned} \tag{5.8}$$

Therefore the feasible condition $\sum_{j=1}^{n+1} d_i = \sum_{i=1}^{m} s_i$ is fulfilled. (5.9)

Section E: These squares, or cells, represent the quantity (xij) of JT's (WC's) that are assigned from the source to the destination. In other words, all x_{ij}'s in Table 5.5 denote the number of JT's (WC's) that are needed to manufacture JS's. The value of each x_{ij} will be either zero or a positive number.

To incorporate necessary data into the Table, the single manufacturing cost (cij) for JT's or WC's is entered in the upper right corner of each square of section E, as shown in Table 5.4. If in a particular solution the value of c is enormously high for a square, this means that the combination of the JT with the JS is not appropriate in terms of manufacturing. The column of the fictitious JS is attached to section E in order to balance the condition $\Sigma\, s_i = \Sigma\, d_j$. For a clear identification of every single cell a JT – JS combination symbol, [1. JT - 1. J.S.], has been inserted.

The following statements and applications of examples for the JTSP are based on the illustrated transportation table of Table 5.4.

According to Zimmermann [1986], the TP in principle could be solved with the simplex method, though not without an immense effort of calculation. However, there is a method of problem solving, called the distribution method that is older and more easily handled than the simplex method. In the following, the procedure of the distribution method is subdivided into four steps.

To / From	1. Joining Side	2. Joining Side	…	n. Joining Side	Fictitious n+1. J. Side	J. Technique Supply s_i
1. Joining Technique	x_{11} 4 1.JT-1.J.S.	x_{12} 6 1.JT-2.J.S.	…	x_{1n} 6 1.JT-n.J.S.	x_{1n+1} 0 1.JT-F.J.S.	$s_1 = \frac{Len_{total}}{Len_{WC}}$
2. Joining Technique	x_{21} 7 2.JT-1.J.S.	x_{22} 100 2.JT-2.J.S.	…	x_{2n} 5 2.JT-n.J.S.	x_{2n+1} 0 2.JT- F.J.S.	…
…	…	…	…	…	…	…
m. Joining Technique	x_{m1} 8 m.JT-1.J.S.	x_{m2} 6 m.JT-2.J.S.	…	x_{mn} 100 m.JT-n.J.S.	$x_{m\,n+1}$ 0 m.JT- F.J.S.	$s_m = \frac{Len_{total}}{Len_{WC}}$
J. Side Demand d_j	$d_1 = \frac{Len_{JS1}}{Len_{WC}}$	…	…	$d_n = \frac{Len_{JSn}}{Len_{WC}}$	$d_{n+1} := \sum_{i=1}^{m} s_i - \sum_{j=1}^{n} d_j$	$\sum_{j=1}^{n+1} d_j$ / $\sum_{i=1}^{m} s_i$

Table 5.4: Transportation table with squares identified and costs for one WC.

***Step 1:* Validation of the balanced condition**

As previously described, the sufficient condition of $\sum s_i = \sum d_j$ has to be validated. This means that if the demand is not equal to the supply, fictitious rows and columns of balance (dummies) have to be inserted into the transportation table. In the case of the JTSP the supply Σs_i of JT's or WC's will always be higher than the demand Σd_j of the JS's. Therefore a fictitious column will be added to the transportation table. The value of this fictitious column must be great to ensure that the column not be taken mathematically as listing a real JS.

***Step 2:* Matrix reduction**

The reduction of the cost matrix is particularly advisable if the optimal solution is to be ascertained by the Stepping-Stone method. Matrix reduction involves less in the way of calculation. Certain rules for matrix reduction prevent the alteration of the distribution problem.

***Step 3:* Constructing an initial basic feasible solution**

As in the case of the simplex method an *initial feasible solution* must be ascertained. There are three methods for obtaining an initial basis and feasible solutions:

a) Northwest-corner rule
b) Minimum-entry method
c) Vogel Advanced Start Method (VAM)

***Step 4:* Determination of the optimal solution**

Having obtained a first feasible solution to the distribution problem, the next step is to determine whether this solution is best in terms of cost. Two alternative procedures for evaluating the optimal solution are available:

a) Stepping-Stone-Method
b) Modified distribution (MODI) method also called υ-ν-method

This latter procedure with its algorithms can be applied to an example of the JT selection problem. Thereby the constraints are coming from the praxis. The application of these constraints is of critical importance if the methodology of the JT selection is to be improved and if further zones of optimisation are to be entered. This will carry into a discussion on the extent to which the JTSP can be resolved by means of the distribution method. In the following, a JTSP example will be explained on the basis of the distribution method. For this purpose the constraint obtains that exactly one JT with a given number of WC's can be distributed to every JS.
Comparison of the example to the real world design process indicates that in practice only one JT with its WC's is applied to one JS. The scarcity of manufacturing space within an automobile plant does not permit equipment for different pieces of Joining Technology machinery in one place. Also the need of space for maintenance would not be met. The cost for investment, maintenance and quality assurance would increase dramatically in the manufacturing process. The assumption acted on is that the distribution of exactly one JT to each JS is unavoidable if manufacturing costs are not exploded.

5.5.2.1 Application of the Transportation Method to the Joining Technique Selection Problem

The following example refers to section 0 where the JTSP was formulated on the basis of a model. This schematic of an automotive wheelhouse with its joining parts, sides and lengths is applicable to real situations. Instead of data pertaining to demand d_j and the supply s_i in the transportation table, data on the JS material and the length may be entered. In the following diagram, these data have been arranged in table form, as shown in Table 5.5.

Joining Side	Material combination	JS Length [mm]	Number of WC's
1. JS	Steel - Steel	500	10
2. JS	Aluminium - Aluminium	250	5
3. JS	Steel - Aluminium	450	9
4. JS	Steel - High tensile Steel	300	6
5. JS	High tensile Steel - Aluminium	350	7

Table 5.5: Examples data for material combination and length of Joining Sides.

Due to the various combinations of the JS materials, the authorised JT's can be defined directly on the basis of the matrix of approved JT's and material combinations given in section 4.6.2. The output quantity of the authorised JT is dependent on the JS length and is specified by the number of WC's.

This conversion ratio is taken from the Joining-Technique cost-tables given in Chapter 4.6.4 and Table 4.5. The demand d_j of the remaining JS's can be converted according to the same pattern.

The supply s_i of WC's of every JT (row) to every single JS (column) is:

$$s_i = \sum_{j=1}^{n} d_j \qquad \text{for } i = 1,2, \ldots, m \qquad (5.10)$$

This constraint is valid for the followings "transportation" examples because a single JT with its fixed number of WC's can supply all JS's.

The cost for a JT with its WC's is a function of the material combination and the complexity level (JS Coefficient) of every JS as already described in section 4.6. In the following example these costs are simplified as shown in Table 5.6 for solving the problem by hand.

C_{ij}	j = 1	2	3	4	5
i = 1	6	5	100	7	100
2	7	6	7	100	6
3	8	7	7	6	8

Table 5.6: Working content cost table for the Joining Technique Selection example.

In this example, the constraints permit the distribution of exactly one JT with a given number of WC's to every JS.

If the data of Table 5.5 and Table 5.6 are entered in the transportation table as shown in Table 5.7, the result will be the JT distribution table.

Once the data have been arranged in table form, an initial feasible solution may be sought with the help of the northwest-corner rule. One initial solution to the JTSP of the example is illustrated in Table 5.7.

In this instance the first and second JS can be supplied with WC's of spot welding, the third JS by clinching and the fourth and fifth JS by blind riveting.

The quality of this initial solution can be indicated by the interim manufacturing cost.

$$Z = \sum_{j=1}^{n}\sum_{i=1}^{m} c_{ij}x_{ij} = 10\times6+5\times5+9\times7+6\times6+7\times8=\underline{\underline{240}}$$

A first solution to the JTSP having been found, the practical applicability of the example chosen may be examined.

Length [mm]	500	250	450	300	350	7400	
Material	Steel - Steel	Alu - Alu	Steel - Alu	Steel-Ht.Steel	Ht.Steel-Alu	fictitious	
From \ To	1. J. S.	2. J. Se.	3. J. S.	4. J. S.	5. J. S.	Fictitious J. S.	J. Technique Supply s_i
1. J. T. Spot welding	6 (10)	5 (5)	100	7	100	0 (6)	21
2. J. T. Clinching	7	6 (0)	7 (9)	100	6	0 (22)	31
3. J. T. Riveting	8	7	7 (0)	6 (6)	8 (7)	0 (24)	37
J. Side Demand d_j	10	5	9	6	7	52	89 \ 89

Table 5.7: Joining Technique distribution table with an initial solution.

In the previous examples, the optimal solution can be determined by means of the fourth step in Zimmermann's procedure, described above, followed by application of the Stepping-Stone-Method or the Modified Distribution method (MODI). This fourth step will not, however, shed light on the question whether the distribution method is applicable to the solution process of the JTSP.

In the following, some of the strengths and weaknesses shown by application to the JTSP of schematics designed for the TP will be passed in review.

5.5.2.2 Discussion and Conclusion about the Application of the Transportation Method to the Joining Technique Selection Problem

An itemisation of strengths and weaknesses in the transformation process by which the Transportation Method is applied to the JTSP may serve as a preliminary to discussion.

Strengths:

- The coefficients: supply of goods and costs are mathematically transferable into the JTSP.
- The number of sources (JT's with their WC's) and the number of destinations (JS's) mathematically are not restricted.
- The layout of the Transportation Table and therewith the layout of the JT distribution table are concise and plain for the user.
- The mathematical approach of the TP is validated by OR procedures accepted worldwide.
- Much OR software is available for solving the TP.

Weaknesses:

- Only one kind of cost for investment, running cost, maintenance etc. can be taken into account.
- As a consequence of that the optimisation algorithm can arrive at sub-optimal solutions.
- The TP permits the distribution of more than one JT, each having a given number of WC's, to the same JS, a case that can hardly arise in practice because of additional robots and lack of space in the BIW factory floor.

At first sight, therefore, the optimisation procedure of a JSTP treated as if it were a TP does not seem to present unresolvable problems. Furthermore the great number of strengths and advantages of the Transportation Method are strong grounds to view it as a desirable approach to the JTSP. The greatest weakness of this approach consists in the fact that the distribution process of the Transportation Method will yield only the technology that will prove cost-saving in the case of every JS, so that the least expensive Joining Technology, assuming an infinite supply of such, would automatically be chosen by the distribution process in every case. This is not a realistic solution to the problem as it would not ensure success to the JTSP. So the TP is mathematically not sufficient to offer adequate solutions to such a complex technical engineering problem as assigning WC's in form of JT to JS because the method is by its nature linear.

A logical step forward will be to use a method that can be implemented to non-linear problems capable of using more than one type of cost. Nevertheless the evaluation and the application of the TP have been another important step for the research work with the determination and mathematical formulation of boundaries and restrictions. This investigation has furthered the search of another suitable OR optimisation process. Such an OR process out of the area of DP will be analysed and discussed in the following section.

5.6 Dynamic Programming adopted to the Joining Technique Selection Problem

According to Edwards [1985], LP problems have one common characteristic: they are static. Problems are stated and solved in terms of a specific situation occurring at a certain moment. When a problem is concerned with variations over time, a different OR technique must be used, one that provides for the time element. Such a technique, called Dynamic Programming, is an extension of the basic Linear Programming technique.

The title "Dynamic Programming" stems from the work of R.E. Bellman and G. B. Dantzig, published largely in Bellman [1957], Bellman and Dreyfus [1962] and Dantzig [1963]. Their important contribution on this quantitative technique was first published in the 1950's. Bellman was the first to appreciate the wide range of applicability of a computational procedure commonly referred to as the *value iteration algorithm*.

Initially, DP was referred to as stochastic LP or LP dealing with uncertainty. Today DP has been developed as a quantitative technique to solve a wide range of business problems [Hastings, 1973].

5.6.1 The Nature of Dynamic Programming

DP has some elements in common with the LP techniques, but it is really only one of the distant cousins of this family. Its distinctive feature is that it deals with a sequence of linked decisions – generally at different points in time, but sometimes at different points in space. Some of its fields of application include multi-period production and inventory planning, choice of shortest route, equipment replacement and even optimal animal feeding problems.

At the heart of all the algorithms for DP is the 'Principle of Optimality' set out by Bellman [1957]. In everyday language, this principle says that if one cuts into the optimal sequence of decisions at any point, the remaining decisions in the sequence will still be the best that could be made from that point onwards. As a result, the optimal solution is usually found by working backwards from the final decision point.

Thierauf [1978] gives the explanation that DP is based on the "principle of optimality," which states that an optimal policy is one that consists of optimal sub-policies. Hillier and Lieberman [1995] emphasise that DP is a useful mathematical technique for making a sequence of interrelated decisions. It provides a systematic procedure for determining the optimal combination of decisions. In contrast to LP, there does not exist a standard mathematical formulation of "the" DP problem. Rather, DP is a general type of approach to problem solving, and the particular equations used must be developed to fit each individual situation. Therefore, a certain degree of ingenuity and insight into the general structure of DP problems is required to recognise when a problem can be solved by DP procedures and how it can be done.

DP may be thought of as a way of looking at a problem containing a large number of interrelated decision variables; it consists in breaking the problem down into a sequence of problems, each of which requires the determination of a small number of variables, or even of a single variable.

This technique is one of the newer tools of operational researchers. As more researchers master the subject matter of DP, it will find wider application.

Shamblin and Stevens [1974] state: "Of all the mathematical tools employed in Operations Research, Dynamic Programming is perhaps the simplest in concept and yet one of the most difficult to apply".

5.6.2 The Process of Dynamic Programming

DP is structured somewhat differently from other OR techniques because it divides the problem into a number of sub-problems or decision stages. General recurrence relations between one stage and the next stage describe the problem. A stage usually refers to a time period but need not necessarily represent time. Also, the state of the system is described by one or more state variables. Within this structural framework, a DP approach is helpful in solving sequences of decisions affecting decisions that must be made in the future. Even though incorrect or less than optimal decisions have been made in the past, DP still enables one to make correct decisions for future periods.

White [1969] asserts that problems to which DP has been applied are usually stated in the following terms. A physical, operational, or conceptual system is considered to progress through a series of consecutive *stages*. At each stage the system can be described or characterised by a relatively small set of parameters called the *state variables* or *state vector*. At each stage, and no matter what state the system is in, one or more decisions must be made. The decisions may depend on either stage or state or both. It is true that the past history of the system, i.e., how it got to the current stage and state, are of no importance. In other words, the decisions depend only upon the current stage and state. When a decision is made, a return (for the minimisation problem "cost" might be a more appropriate term) or reward is obtained and the system undergoes a *transformation* or *transition* to the next stage.

The overall purpose of the staged process is to maximise or minimise some function of the state and decision variables. The key elements that one associates with a DP problem are stages, states, decisions, transformations, and returns.

Ideally, what DP seeks to do is, in effect, solve *n* single variable problems instead of a single problem with *n* variables. Whenever this is possible, it usually requires much less computational effort. Solving *n* smaller problems requires a computational effort that is proportional to *n*, the number of single variable problems if each problem contains one

variable. On the other hand, solving one larger problem with *n* variables usually requires a computational effort roughly proportional to a^n, where *a* is some constant.
Hence the desirability of transforming or considering an *n*-dimensional problem as *n* one-dimensional problems.

5.6.3 The Capital Budgeting Problem applied to the Joining Technique Selection Problem

The Capital Budgeting Problem (CBP) represents a typical allocation problem in which, generally, resources are to be optimally distributed among a number of activities (stages) [Taha, 1992]. The definition of the state of the system for all allocation problems is generally the same: namely, the quantity of the resource (JT's) allocated to a successive number of stages (JS's) starting from the last or the first stage depending on whether the backward or the forward method has been chosen.
According to Hastings [1973], in an allocation problem a limited supply of one or more resources, such as raw materials, capital, labour, time, space, carrying capacity, etc., is to be allocated to a number of uses in such a way as to optimise some objective function.
The method of solution for the JTSP can be the Capital Budgeting Method. It is one of the computational algorithms of DP. For that the JTSP has to be re-written in terms of the CBP:

Minimise

$$\begin{aligned} M(k_1, ..., k_N) &:= M_1(k_1) + ... + M_N(k_N) \\ &= \sum_{j=1}^{N} M_j(k_j) \end{aligned} \tag{5.11}$$

so that

$$\sum_{j=1}^{N} c_j(k_j) \le C \tag{5.12}$$

k_j := Number of proposed JT at JS j
$M_j(k_j)$:= Manufacturing costs of JS j under proposal k_j
$M(k_1, \ldots, k_N)$:= Total manufacturing cost of all JS's under the proposals $k_1, \ldots, k_N$
$c_j(k_j)$:= Investment cost at JS j under proposal k_j
C := Approved investment budget

In the following the Capital Budgeting Methodology can be applied to the JTSP. The algorithm is given by the following *recursive equations*:

$$f_1(x_1) := \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \{ M_1(k_1) \} \tag{5.13}$$

$$\begin{aligned} f_j(x_j) &:= \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \{ M_j(k_j) + f_{j-1}(x_j - c_j(k_j)) \} \\ &= \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \{ M_j(k_j) + f_{j-1}(x_{j-1}) \} \qquad \text{with: } j = 2,3,\dots,N \end{aligned} \tag{5.14}$$

x_j := Amount of investment allocated to JS 1, ..., JS j
$f_j(x_j)$:= Sum of optimal manufacturing cost for JS 1, ..., JS j

In words the algorithm can be written as:

Value of iterative stage (step) j := **Minimum over all feasible proposals for stage (step) j** [**Returned value for a stage (step) j proposal** + **Value of iterative stage (step) j-1**]

When the current stage number j-1 is increased by one, the new $f_j(x_j)$ value is calculated by means of the $f_{j-1}(x_{j-1})$ value calculated during the preceding iteration, and this process keeps repeating.

The iterative process ends with N and the according value $f_N(x_N)$ provides the sum of optimal manufacturing costs. The chosen feasible JT's from stage (step) 1 to stage (step) N yield an optimal solution for the JTSP. If at the end of the calculation, stage (step) N, there is more than one feasible solution, each with its overall manufacturing cost, then, obviously, the solution with the lowest investment cost is chosen.

Note that the problem need not have a feasible solution at all. If there is none, it will be recognised that there is no feasible solution in the iterative steps.

DP problems are reversible in the sense that the solution procedure actually could have moved either backwards or forwards (the latter alternative amounts to renumbering the stages in reverse order and then applying the procedure in the standard way). This reversibility is a general characteristic of resource distribution problems.

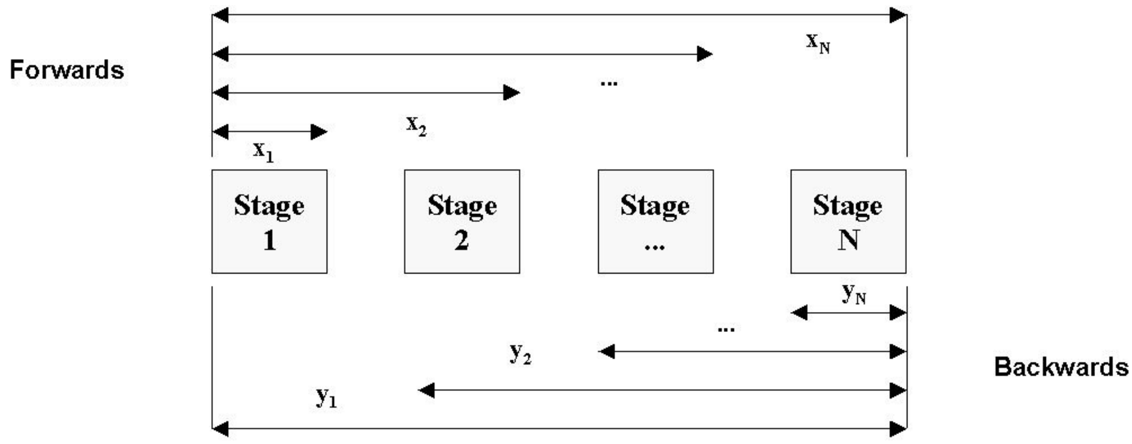


Figure 5.6: The basic structure for forward and backward DP procedures.

According to Hillier and Lieberman [1988], for some problems, especially when the stages (steps) correspond to time periods, the solution procedure must move backward. The definition of state x_j and y_j in the forward and backward methods can be compared graphical summaries of both given in Figure 5.6.The Capital Budgeting Method applies generally, though with variations in detail, to sequential problems over a wide range of applications.

The flow chart for the algorithm is shown in Figure 5.7. It has three loops. The inner loop (loop 3) corresponds to finding the best action at a state. The middle loop (loop 2) takes the procedure from one state to another at each stage, whilst the outer loop (loop 1) takes the procedure over each stage in turn. By following the flow chart, one can determine the optimal action and value for every state.

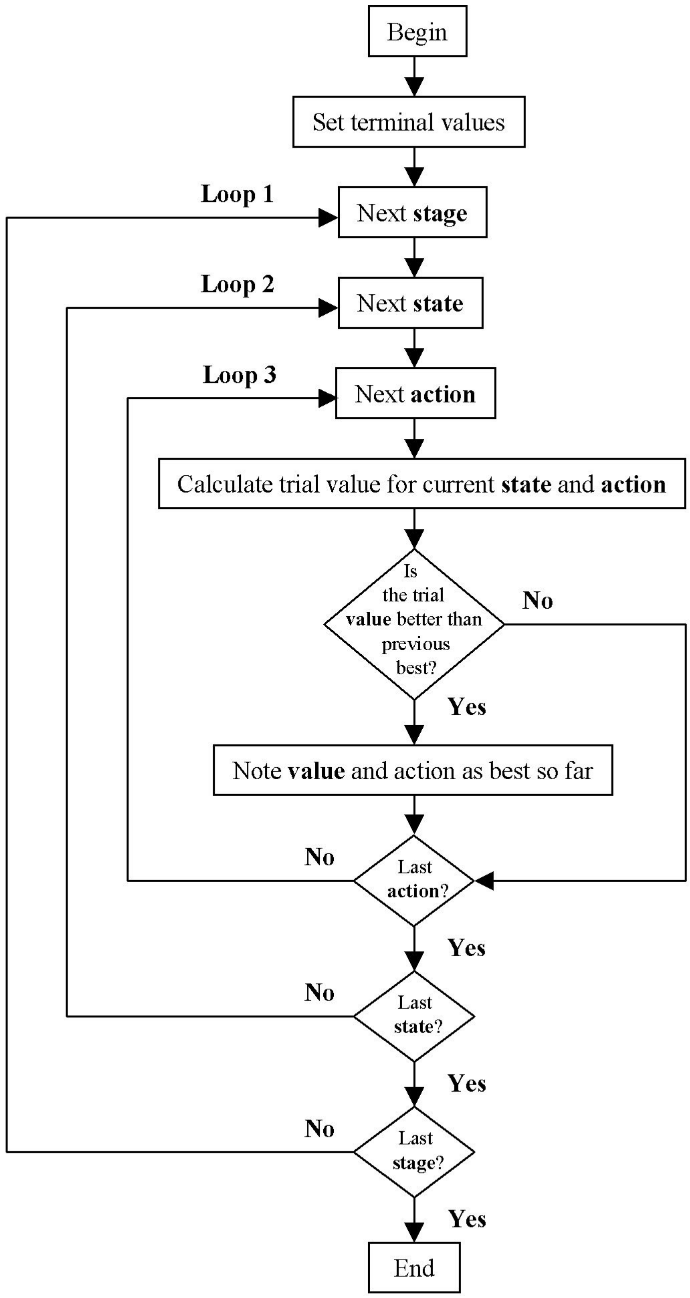


Figure 5.7: DP flow chart for the Capital Budgeting Method.

5.6.3.1 Application of the Capital Budgeting Method to the JTSP

The connection between stages and states in the JTSP has always been described in the previous section. As indicated in Table 5.8: Two-resource allocation problem., each JS represents a stage at which it must be decided which JT is optimal. The alternatives are given by the decision variable k_j at stage j, which designates the Joining Technology. In this case the manufacturing cost function is $M_j(k_j)$. The stages are "linked" by the fact that all the JS's (stages) are in competition for the optimal JT, hence for a share of the limited investment budget C.

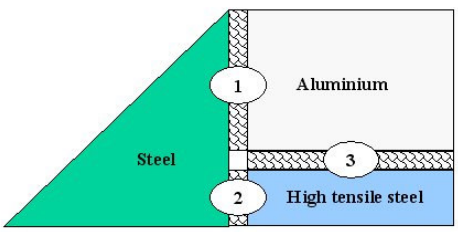
	Allocation of Joining Techniques [€]	Target							
		1. Joining Side		2. Joining Side		...		n. Joining Side	
		c_1	M_1	c_2	M_2	...	...	c_n	M_n
Source	1. Joining Technique	c_{11}	M_{11}	c_{21}	M_{21}	...	...	c_{n1}	M_{n1}
	2. Joining Technique	c_{12}	M_{12}					...	...
	...	...	...					...	...
	m. Joining Technique	c_{1m}	M_{1m}	...	...	...	...	c_{nm}	M_{nm}
		stage 1		stage 2		stage 3		stage n	

Table 5.8: Two-resource allocation problem.

Transformation of the JTSP occurs as follows. The car body produced by an automotive BIW production involves a certain number of joining operations. Each car body requires a number of different JT's for joining the blank sheets together. Allocation of a certain number of JT's to a certain number of JS's determines the manufacturing cost. The possible allocating investment cost c for the Joining Technologies is restricted by an approved investment budget C. The aim is to find the optimal combination of JT's that will provide minimum manufacturing cost.

The purpose of the following JTSP example is to show that the CBP is an appropriate method for finding the optimal manufacturing cost solution.

A BIW project comprises the manufacturing of around 20.000 units of steel – aluminium compound, as shown in Figure 5.8.



	Material	J.S. length [mm]
1. Joining side	Aluminium – Steel	400
2. Joining side	Steel – High tensile steel	250
3. Joining side	Aluminium – High tensile steel	550

Figure 5.8: Schematic of steel – aluminium compound with joining parts, sides and length.

Therefore the investment cost of 920,000 EUR for the purchase of 3 joining machines has been approved. As revealed in the illustration of Figure 5.8 the number of JS's is 3. The constraint of the limited investment budget of 46 EUR for every single compound results from the approved investment budget. The following calculation of the CBP provides evidence that this method is suited to optimise the manufacturing cost under the predetermined constraints.

Example for the JTSP:

Minimise $M(k_1, k_2, k_3) = M_1(k_1) + M_2(k_2) + M_3(k_3)$ (5.15)

so that $C = c_1 + c_2 + c_3 \leq 46$ EUR (5.16)

DP forward procedure:

$$f_1(x_1) := \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \left\{ M_1(k_1) \right\} \tag{5.13}$$

$$f_j(x_j) := \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \left\{ M_j(k_j) + f_{j-1}(x_{j-1}) \right\} \quad \text{with:} \quad j = 2,3 \tag{5.14}$$

Computation of the Capital Budgeting Method must proceed on the basis of proper data concerning investment cost c_j and manufacturing cost M_j. These cost data are gathered in the JT cost templates that are specified in Chapter 4.6.4, attached in the Appendix 7, and used for the CBP source matrix, as shown in Table 5.9.

Joining side No.:		1		2		3	
Joining Side Length [mm]:		400		250		550	
Joining Side Material:		Steel - Aluminium		Steel – High tensile steel		Aluminium – High tensile steel	
No.	**Joining Technique** / **Costs**	c_1	M_1	c_2	M_2	c_3	M_3
1.	Spot welding	12	2,5	14	2,5		
2.	MIG welding	16	2	14	1,5		
3.	Punch riveting	14	2,5			12	2
4.	Cohesiveness gluing	18	1,5	20	1	18	1,5

Table 5.9: Source matrix of the CBP for a concrete JTSP example.

This CBP source matrix visualises the acquisition of every single JS with its length and material combination. In addition, the authorised JT's are arranged in lines with associated cost of investment c and manufacturing M.

As was mentioned in the algebraic statements (5.14) the DP *forward method* is chosen for the solution of the transformed JTSP. For this purpose the calculation procedure starts with the stage 1.

Application of the equation (5.13) yields the optimal solution for the manufacturing cost of JS 1. This optimal solution can be read directly from Tableau in Table 5.10. The optimal value for $f_1(x_1)$ is 1,5 EUR and specifies for the 1st JS the application of JT cohesiveness – gluing, which is embodied by the proposal vector [4], as indicated in Table 5.10. This done, the procedure moves on to state 2.

State 1	**Manufacturing cost for feasible proposals: $M_1(k_1)$**				**Optimal solution**		
x_1 [€]	k_1=1	k_1=2	k_1=3	k_1=4	$f_1(x_1)$	Proposal number	Proposal Vector
12	2,5	--	--	--	2,5	1	[1]
14	2,5	--	2,5	--	2,5	1 or 3	[1] or [3]
16	2,5	2	2,5	--	2	2	[2]
18	2,5	2	2,5	1,5	1,5	4	[4]
20	2,5	2	2,5	1,5	1,5	4	[4]
22	2,5	2	2,5	1,5	1,5	4	[4]
24	2,5	2	2,5	1,5	1,5	4	[4]
26	2,5	2	2,5	1,5	1,5	4	[4]
28	2,5	2	2,5	1,5	1,5	4	[4]
30	2,5	2	2,5	1,5	1,5	4	[4]
32	2,5	2	2,5	1,5	1,5	4	[4]
34	2,5	2	2,5	1,5	1,5	4	[4]
36	2,5	2	2,5	1,5	1,5	4	[4]
38	2,5	2	2,5	1,5	1,5	4	[4]
40	2,5	2	2,5	1,5	1,5	4	[4]
42	2,5	2	2,5	1,5	1,5	4	[4]
44	2,5	2	2,5	1,5	1,5	4	[4]
46	2,5	2	2,5	1,5	1,5	4	[4]

Table 5.10: Computation tableau for state 1 of the JTSP example.

The calculations carried out by function (5.17) also seek a conditional optimal solution for stage 2 as a function of the state x_2 in compliance with the constraint (5.16).

$$f_2(x_2) = \min\{M_2(k_2) + f_1(x_2 - c_2(k_2))\} \qquad \text{with: } k_2 = 1, 2, 3, 4 \qquad (5.17)$$

However, they differ from those of stage 1 in that state 2 now defines the investment budget to be allocated to stage 1 and stage 2. Such a definition will guarantee that a decision made for stage 2 will be automatically feasible for stage 1.

Therewith the temporary optimal solution for the manufacturing cost of the calculations for stage 2 is $f_2(x_2)$ = 2,5 EUR. The proposal vector [4, 4] specified the application of cohesiveness gluing for both JS's as a conditional optimal solution.

With application of function (5.18) the third and last step of the JTSP example yields the final optimal solution.

$$f_3(x_3) = \min\{M_3(k_3) + f_2(x_3 - c_3(k_3))\} \qquad \text{with: } k_3 = 1, 2, 3, 4 \qquad (5.18)$$

State 2	Manufacturing cost for feasible proposals: $\{M_2(k_2) + f_1(x_2 - c_2(k_2))\}$				Optimal solution		
x_2[€]	k_1=1	k_1=2	k_1=3	k_1=4	$f_2(x_2)$	Proposal number	Proposal Vector
26	2,5+2,5=5,0 [1]	1,5+2,5=4,0 [1]		--	4,0	2	[1, 2]
28	2,5+2,5=5,0 [1] 2,5+2,5=5,0 [3]	1,5+2,5=4,0 [1] 1,5+2,5=4,0 [3]		--	4,0	2	[1, 2] or [3, 2]
30	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3]		--	3,5	2	[2, 2]
32	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1]	3,0	2	[4, 2]
34	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,5=3,5 [3]	3,0	2	[4, 2]
36	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,0=3,0 [2] 1,0+2,5=3,5 [3]	3,0	2 or 4	[4, 2] or [2, 4]
38	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,0=3,0 [2] 1,0+2,5=3,5 [3] 1,0+1,5=2,5 [4]	2,5	4	[4, 4]
40	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,0=3,0 [2] 1,0+2,5=3,5 [3] 1,0+1,5=2,5 [4]	2,5	4	[4, 4]
42	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,0=3,0 [2] 1,0+2,5=3,5 [3] 1,0+1,5=2,5 [4]	2,5	4	[4, 4]
46	2,5+2,5=5,0 [1] 2,5+2,0=4,5 [2] 2,5+2,5=5,0 [3] 2,5+1,5=4,0 [4]	1,5+2,5=4,0 [1] 1,5+2,0=3,5 [2] 1,5+2,5=4,0 [3] 1,5+1,5=3,0 [4]		1,0+2,5=3,5 [1] 1,0+2,0=3,0 [2] 1,0+2,5=3,5 [3] 1,0+1,5=2,5 [4]	2,5	4	[4, 4]

Table 5.11: Computation tableau for state 2 of the JTSP example.

With $f_3(x_3)$ = 5,0 EUR the optimal manufacturing cost has been computed in compliance with the constraint that the approved investment budget of C ≤ 46 EUR not be exceeded, as shown in Table 5.12.

State 3	Manufacturing cost for feasible proposals: $\{M_3(k_3) + f_2(x_3 - c_3(k_3))\}$				Optimal solution		
x_3 [€]	k_1=1	k_1=2	k_1=3	k_1=4	$f_3(x_3)$	Proposal number	Proposal Vector
38			2,0+4,0=6,0 [1, 2]	--	6,0	3	[1, 2, 3]
40			2,0+4,0=6,0 [1, 2] 2,0+4,0=6,0 [3, 2]	--	6,0	3	[1, 2, 3] or [3, 2, 3]
42			2,0+4,0=6,0 [1, 2] 2,0+4,0=6,0 [3, 2] 2,0+3,5=5,5 [2, 2]	--	5,5	3	[2, 2, 3]
44			2,0+4,0=6,0 [1, 2] 2,0+4,0=6,0 [3, 2] 2,0+3,5=5,5 [2, 2] 2,0+3,0=5,0 [4, 2]	1,5+4,0=5,5 [1, 2]	5,0	3	[4, 2, 3]
46			2,0+4,0=6,0 [1, 2] 2,0+4,0=6,0 [3, 2] 2,0+3,5=5,5 [2, 2] 2,0+3,0=5,0 [4, 2]	1,5+4,0=5,5 [1, 2] 1,5+4,0=5,5 [3, 2]	5,0	3	[4, 2, 3]

Table 5.12: Computation tableau for state 3 of the JTSP example.

As another result of the calculation the final proposal vector [4, 2, 3] can be gathered from the computation tableau of state 3. This vector itemises the optimal selection of the JT's to JS's as represented in the solution Table 5.13.

If the optimal singular solution for manufacturing cost is identified with the proposal vector [4, 2, 3], the monetary value of the definitive investment cost C can be calculated.

Proposal vector of the optimal solution	1. Joining Side	2. Joining Side	3. Joining Side	Investment cost C per compound	Manufacturing cost M per compound
[4, 2, 3]	Cohesiveness gluing	MIG welding	Punch riveting	44,0	5,0

Table 5.13: Solution Tableau for the JTSP example.

For greater clarity, the optimal solution vector [4, 2, 3] yielded by the Capital Budgeting Methodology is included in the source matrix, as illustrated in Table 5.14.

Joining side No.:		1		2		3	
Joining Side Length [mm]:		400		250		550	
Joining Side Material:		Steel - Aluminium		Steel – High tensile steel		Aluminium – High tensile steel	
No.	**Joining Technique** / **Costs**	c_1	M_1	c_2	M_2	c_3	M_3
1.	Spot welding	12	2,5	14	2,5	--	--
2.	MIG welding	16	2,0	14	1,5	--	--
3.	Punch riveting	14	2,5	--	--	12	2,0
4.	Cohesiveness gluing	18	1,5	20	1,0	18	1,5

Table 5.14: Source matrix with the optimal manufacturing cost solution.

Computing the JTSP by means of the CBP has shown the feasibility of finding the optimal manufacturing cost with the appropriate total investment costs. Additionally the proposal vector provides the solution for the optimal combination of JT's.

In the following, the conclusion, that the Capital Budgeting Methodology can be used for the solution process of the research work, will be discussed.

5.7 Appraisal and Discussion of the Results

In section 5.2.4 it became apparent that the JTSP belongs to the category of assignment problems, one of the categories belonging to the area of OR. An investigation of the OR research models and problems, see Figure 5.4, reveals that the JTSP belongs to the category of deterministic, algorithms models. Within the deterministic category the LP with the TP and the DP with the CBP were chosen because they are transferable to JTSP. Hence, in sections 5.5.2 and 5.6.3 the JTSP was transferred into TP and CBP models. On the basis of elaborate enquires into the attributes of the TP and the CBP, realistic calculation examples have been computed. These elaborations of the JTSP with the aid of the solution methodology of TP and CBP yield results helping to decide which optimisation method is more convenient to the research problem.

Application of the TP process to the JTSP has yielded the following results. The main features of the TP can be utilised for the JTSP. The basic idea of transferring JT's into transport goods that have to be transported from the source to the destination (JS's) under the objective of minimum transportation cost (manufacturing cost) turns out to have been fundamentally right. The first calculated examples show reasonable solutions. The accomplishment of more complex examples has yielded the main weakness of the methodology that the involvement of more than one cost type is not possible.

The application of the arithmetical operation of the CBP calculation yields proper optimal solutions, and the verification of the findings are promising. The Capital Budgeting Methodology fulfils the requirements of the JTSP for all intents and purposes such as the possible large-scale of JS's, the utilisation of different cost types or the lucidity of the solution parameters etc. The CBP is an approved and established assignment optimisation problem that solves the JTSP effectively. Furthermore the

CBP methodology is in satisfactory agreement with the results obtained by computation. Therefore the CBP is the appropriate candidate for solving the JTSP, an important part of the overall cost estimation method.
For the evaluation of further arithmetical checks of the CBP and the validation of previous results the accomplishment of an industrial case study out of the automotive industry will be carried out in Chapter 6.
In the following, a systematic model for the manufacturing cost estimation is developed that will be applied in the industrial case study.

5.8 Cost Estimating Model

To complement the results of the JTSP obtained in previous sections, it will be convenient to view the entire cost estimating model as divided into three separate steps, all pertaining to data: analysing, gathering and computing. This model comprises all pertinent information and results obtained by the methodology research work essential for solving the JTSP by means of DP. In effect, such a cost estimating model provides a "recipe" for the solution procedure, which can be used systematically by the BIW design engineer.

1. Step: Once a design concept of a new design task is completed, the design drawings and supporting documents are analysed within sub-step 1a). The data obtained define every single JS with its Joining Materials combination, its JS Length and the required number of WC's. These acquired relevant data are gathered in the JS Material, JS Length and WC's Table within sub-step 1b), as indicated in the previous Chapter.
Afterwards the significant technical data for the JTSM are concentrated in the Basic Source Matrix, which leads to the second step of the procedure.
In the future, linking the data from the digital design concept in a standard CAD program like CATIA to the JS Material, JS Length and WC's Table by means of a customised software program could lead to automation of Step One.

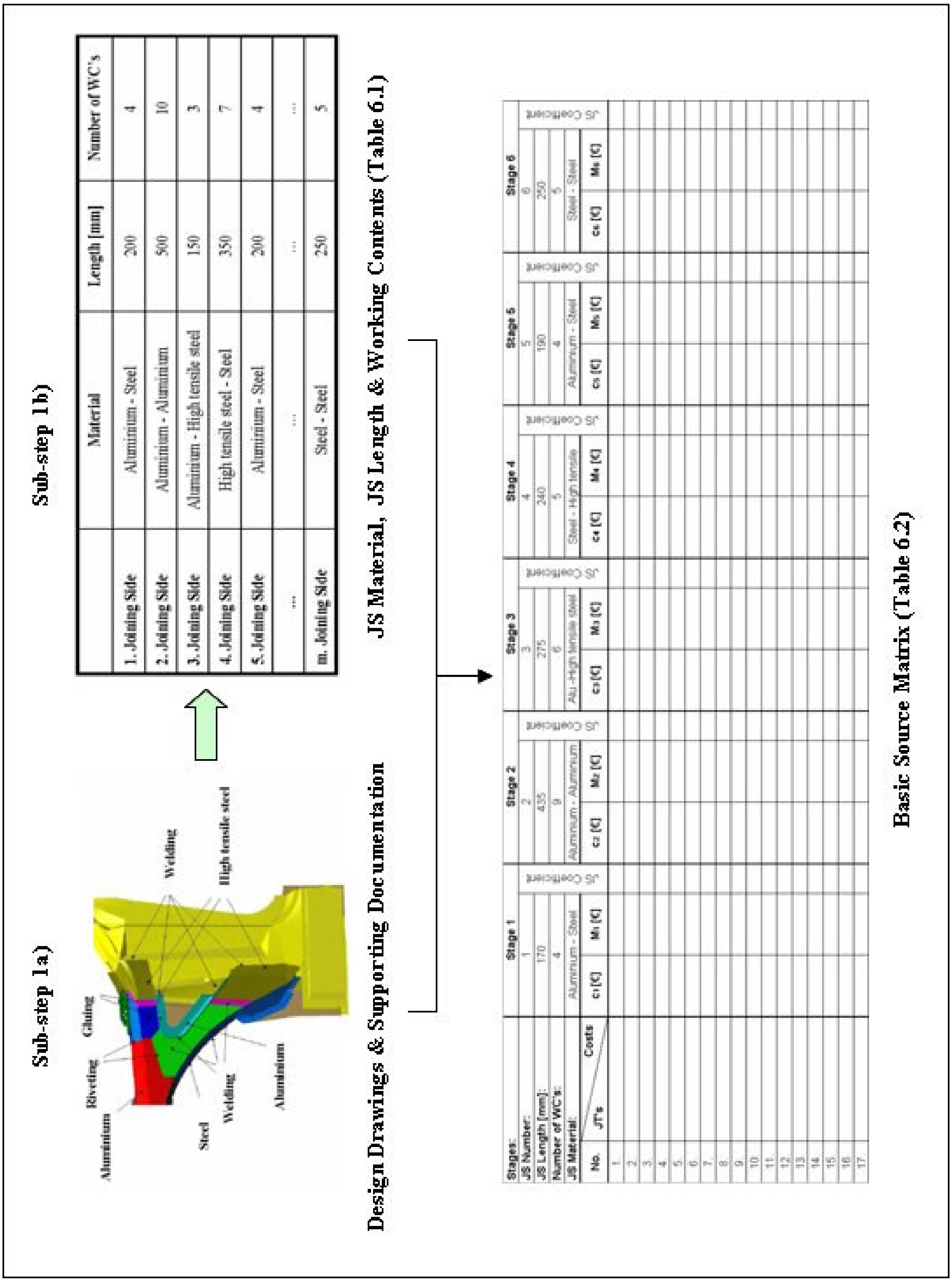


Figure 5.9: First Step: Analysis and gathering of technical data.

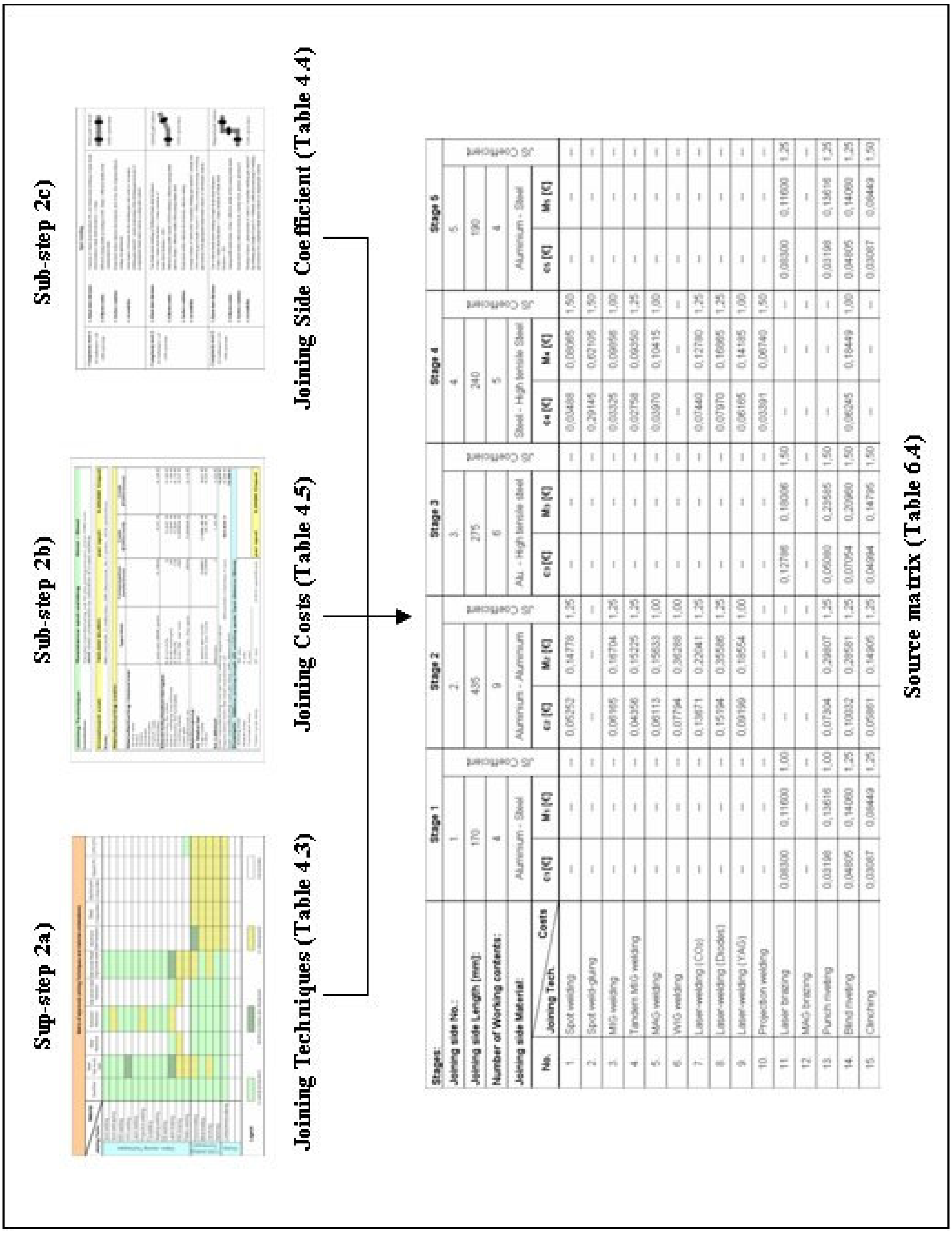


Figure 5.10: Second Step: Analysis and gathering of economic data and completion of the Source Matrix.

2. Step: The decisive technical data of the new design concept having been analysed in Step One, Step Two appraises mainly the crucial economic data of the JT's and allocates them to the individual JS's. For this purpose the matrix of approved JT's and material combinations are used first. It yields the authorised JT's and assigns them to JS's already defined. Then, when the assigned JS lengths and the JT cost templates are consolidated, the assigned investment and manufacturing cost of every single JS can be established as shown in Chapter 4.

In sub-step 2c) the defined JS's are evaluated in terms of the technical practicability of the chosen authorised JT's. Elaboration of the JSC requires that complexity levels be joined with tables defining and itemising the boundaries of technical difficulties pertinent to cycle time. This coefficient includes the variations of cycle time associated with investment and manufacturing costs. Multiplying the costs of the respective JT's by this coefficient yields the cost modifications desired.

The cost assigned the individual JS's is the basis for the completion of the Source Matrix, which is the linchpin for the computation process of the JTSM. Supplemented by the JS lengths and the JS material combinations, the matrix visualises the individual data of every JS in the investigated design concept. Generating the Source Matrix transforms the JS's into stages, which are a basis requirement for computation of the JTSM by means of DP.

Like Step One, Step Two can be automated by a software tool, which can automatically complete the Source Matrix by consulting the approved JT material combinations matrix, the JT cost templates and the JSC tables.

3. Step: Once all crucial technical and economic data are centralised in the Source Matrix and all JS's are transformed into stages, the real DP process can begin; it involves application of the recursive equations (5.13) and (5.14).

The process is accomplished in stages. Its overall purpose is to ascertain the optimal manufacturing cost of the BIW design concept under consideration on the basis of the combination of JT's and the number of SWC's involved (see Chapter 5.6), and to determine whether this cost can be made to comply with investment budget requirements.

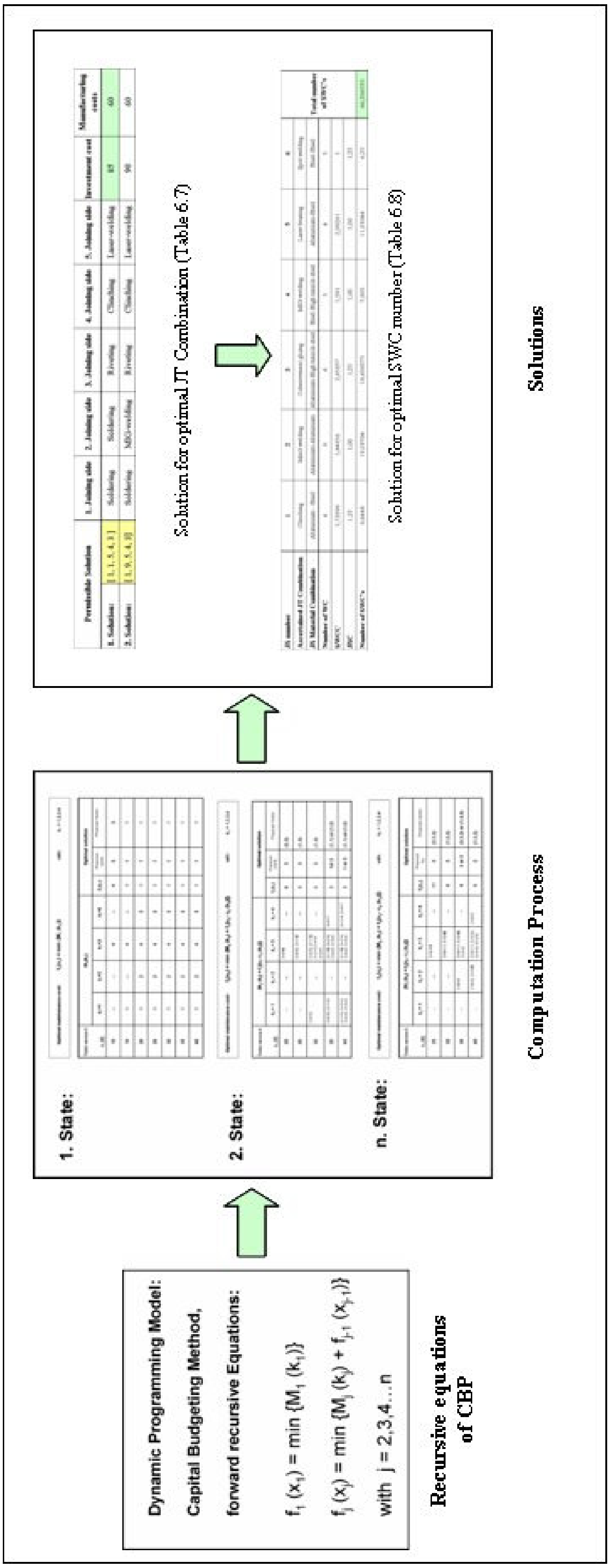


Figure 5.11: Third Step: Computation of the JTSP by means of DP.

The computation procedure depicted provides the optimal combination of JT's for the design concept under scrutiny in terms of minimised manufacturing costs and compliance with the technical and economic boundary conditions.
Once the equations and algorithms of the DP computation process are given, nothing stands in the way of a customised software tool programmed to compute the optimal solution in compliance with the source matrix.

5.9 Summary

Chapter 5 comments on the generation and development of cost based methodology for solving the Joining Technique selection problem.
As a first elementary step of investigation development of the cost model, a basic modelling process, is presented as a basis for development of the cost estimation model. In accordance with this process the problem of selecting the appropriate Joining Technique is described in detail and formulated as a generic model. Subsequently in connection with the Body-in-White Joining Technique selection process an algorithm is developed showing that the Joining Technique Selection Problem is located in the area of assignment optimisation problems. This conclusion led to the area of Operational Research optimisation processes. A further investigation of Operational Research models and problems led to the result that the Joining Technique Selection Problem belongs to the category of deterministic, algorithmic models. These models offer feasible solution methods for the development of a cost based methodology for optimal Joining Technique selection. Further enquiries into optimisation methodologies of Operations Research have confirmed that the *Transportation Problem*, which belongs to the field of Linear Programming, offers a suitable methodology for solving the research objective of ascertaining the optimal manufacturing cost. For that purpose computation of realistic examples with their boundaries and restrictions show that the main features of the *Transportation Problem* can be utilised for the Joining Technique selection problem. Further analysis of deterministic models showed that the *Capital Budgeting Problem* in the methodologies of Dynamic Programming can be used to solve the Joining Technique selection problem. An example of realistic calculation from the automotive industry yields the solutions desired. Subsequently a resume of the results obtained in the

appraisal and discussion section of this chapter leads to the conclusion that Dynamic Programming with the Capital Budgeting Problem and its characteristics is the most appropriate method for solving the Joining Technique Selection Problem. For the evaluation of further arithmetical checks of the *Capital Budgeting Problem* and the validation of previous results the accomplishment of an industrial case study taken from the automotive industry is carried out in Chapter 6.

Finally an entire cost estimating model involving all pertinent information and results obtained by the methodology research work was elaborated. This model, which is divided into three steps, is aimed at providing BIW Design with the option of selecting the most cost efficient Joining Technique combination and thereby ascertaining the relative manufacturing cost of new design concepts.

6 Case Study of Cost Estimation Methodology

6.1 Introduction

Subsequent to the development of the Cost Estimation Procedure in the previous Chapter a further enquiry and evaluation of this methodology will be conducted in the following, in which an effort is made to justify its practicability, its accuracy, and its benefit. For this purpose an Industrial Case Study is presented of an actual design concept taken from the area of automotive Body-in-White and is computed by means of the Joining Technique selection methodology. The Case Study will be solved in two ways: first by means of the conventional methodology, and second with optimisation methodology. These results and findings will be discussed to validate the methodology.

6.2 Industrial Case Study

6.2.1 Introduction

The primary purpose of an Industrial Case Study is to verify a methodology by consideration of a practical example permitting validation or re-assessment of the theory tested. In the course of this scrutiny, the overall methodology has been examined and new insights into the entire process have been analysed and evaluated. This evaluation makes a contribution to the improvement and optimisation of the JTSM developed. In the same way the predefined boundary conditions of the methodology are reapplied and possible variations can be identified and revised.

By application of the Industrial Case Study further advantages and disadvantages of the JTSM are recognised and itemised. Thereby required information about strengths and weaknesses of the generated methodology are obtained. Accordingly, the field of application can be more precisely assigned, whereby the user of the methodology can identify cases in which the user can obtain results suited to be of use in cost estimation. Implications of the methodology can also be appraised to the extent to which it may prove advantageous for computing optimal manufacturing cost.

An actual example taken from the area of automotive BIW is elaborated in the following Case Study. For this purpose real sheet metal components of a front-end wheelhouse have to be joined together with a view to finding the optimal manufacturing cost. First the manufacturing and investment costs are ascertained in a conventional manner. This implies, that the JT's for the joining process of a finished design concept are already defined by the design department. Afterwards the manufacturing costs of the same design concept are estimated by means of the JTSM. In this case the JT's are optimally assigned to the JS's in terms of manufacturing cost and in compliance with the technical and economic boundary conditions.

The findings and results of the Industrial Case Study are evaluated and discussed as follows.

6.2.2 Accomplishment of the Industrial Case Study

The following Industrial Case Study cites as a case in point a BIW design concept. Once the designer has designed the components of a design concept by means of CAD tools, suitable JT's must be assigned to the JS's. The present design concept shows an assembly made up of five individual sheet components. These components are composed of three different joining materials: steel, high tensile steel and aluminium. The Joining sequences of the individual sheet components, as illustrated in Figure 6.1, have been defined by the design department.

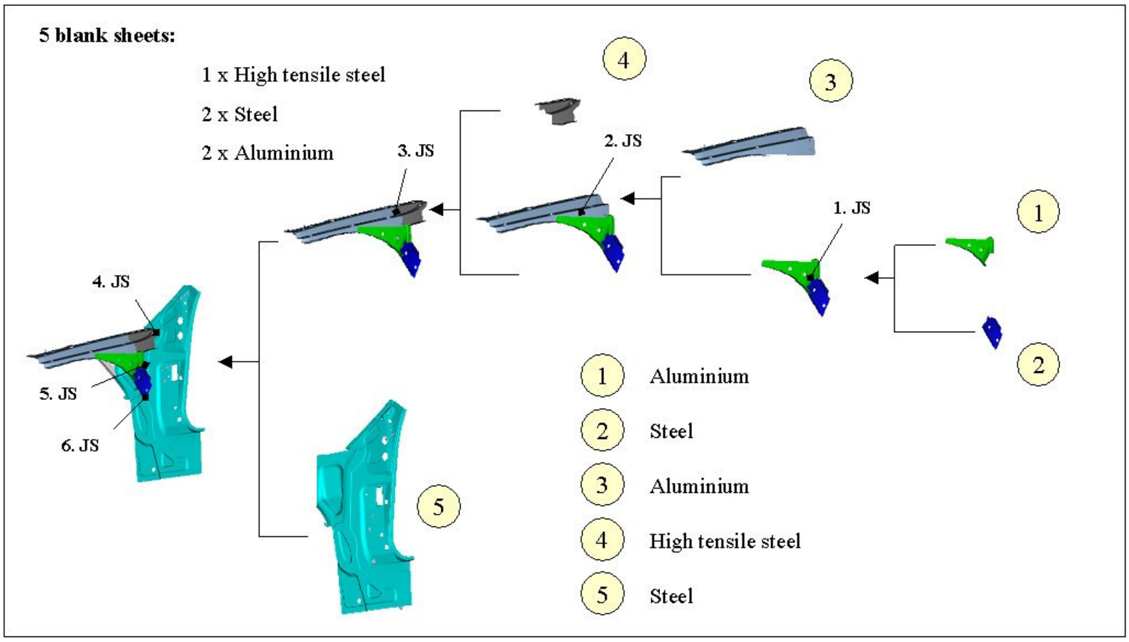


Figure 6.1: Joining cycle of a BIW wheelhouse of the Industrial Case Study.

Analysis of the assembly drawings shows that there are six JS's, as indicated in the above joining cycle, with various Joining Material combinations. By means of the CAD tools the JS lengths can be specified from the design drawings, and the JS Materials, Lengths and WC's Table can be filled in. Hence, the number of WC's derived from the JS length can be ascertained and entered in the Basic Source Matrix.

When the JS Materials, Lengths and WC's Table have been entered as in Table 6.1, step one of the JT Selection Procedure has been completed.

	Material	Length [mm]	Number of WC's
1. Joining Side	Aluminium - Steel	170	4
2. Joining Side	Aluminium - Aluminium	435	9
3. Joining Side	Aluminium - High tensile steel	275	6
4. Joining Side	High tensile steel - Steel	240	5
5. Joining Side	Aluminium - Steel	190	4
6. Joining Side	Steel - Steel	250	5

Table 6.1: JS Materials, JS Lengths and number of WC's Table of the Case Study.

In subsequent steps of the JT Selection Procedure, the question of Joining Material combinations is of critical importance.

Stages:		**Stage 1**			**Stage 2**			**Stage 3**			**Stage 4**			**Stage 5**			**Stage 6**		
JS Number:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
JS Length [mm]:		170			435			275			240			190			250		
Number of WC's:		4			9			6			5			4			5		
JS Material:		Aluminium - Steel			Aluminium - Aluminium			Alu.-High tensile steel			Steel - High tensile			Aluminium - Steel			Steel - Steel		
No.	**JT's / Costs**	**c_1 [€]**	**M_1 [€]**		**c_2 [€]**	**M_2 [€]**		**c_3 [€]**	**M_3 [€]**		**c_4 [€]**	**M_4 [€]**		**c_5 [€]**	**M_5 [€]**		**c_6 [€]**	**M_6 [€]**	
1.																			
2.																			
3.																			
4.																			
5.																			
6.																			
7.																			
8.																			
9.																			
10.																			
11.																			
12.																			
13.																			
14.																			
15.																			
16.																			
17.																			

Table 6.2: Basis Source Matrix of the 6 JS's Industrial Case Study.

In subsequent steps of the JT Selection Procedure, the question of Joining Material combinations is of critical importance. Analysis of the joining sequences in the wheelhouse Case Study leads to identification of five different Joining Material combinations:

1) Aluminium - Steel
2) Aluminium - Aluminium
3) Aluminium - High tensile steel
4) Steel - High tensile steel
5) Steel - Steel

On the basis of the matrix of approved JT's and material combinations, authorised JT's can be assigned their respective JS's. Following the JT Selection Procedure the first joining material combination 1) Aluminium-Steel serves six authorised JT's, as traceable from Table 6.3.

Matrix of approved Joining Techniques and material combinations

	Joining Techn. \ Material	Steel/Steel	Steel/ High tensile steel	Steel/ Aluminium	Aluminium/ Aluminium	High tensile steel/ Aluminium	High tensile Steel/ High tensile steel	Aluminium/ Steel-Sandwich	Steel/ Composites	Aluminium/ Composites	Steel/CFK	CFK/CFK
Warm Joining Techniques	1. Spot welding	in serial production	in serial production		in serial production		in serial production	in development	in development			
	2. Spot weld-gluing	in serial production	in serial production		in development		in serial production	in development	in development			
	3. MIG welding	in serial production	in serial production		in serial production		in serial production					
	4. Tandem MIG welding	in serial production	in serial production		in serial production		in serial production					
	5. MAG welding	in serial production	in serial production		in serial production		in serial production					
	6. WIG welding	in serial production	technical bases are developed		in serial production		in serial production					
	7. Laser welding (CO_2)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	8. Laser welding (Diodes)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	9. Laser welding (YAG)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	10. Projection welding	in serial production	in serial production		in development		in serial production					
	11. Laser brazing	in serial production	technical bases are developed	in serial production	in development	in serial production	technical bases are developed					
	12. MAG brazing	in serial production	in development	in development		in development	in development					
Cold Joining Techniques	13. Punch-riveting	in serial production	in development	in serial production	in serial production	in serial production	in development	technical bases are developed	technical bases are developed	technical bases are developed	in development	in development
	14. Blind-riveting	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
	15. Clinching	in serial production	in development	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development	in development
	16. Flanging	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
Gluing	17. Cohesiveness-gluing	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development

Legend: in serial production; technical bases are developed; in development; not possible

Table 6.3: Matrix of approved Joining Techniques and material combinations.

Once the remaining authorised JT's of the four joining material combinations on the left hand side are determined, they are listed in the Source Matrix, see Table 6.4.

When the authorised JT's have been determined, the JT investment and manufacturing costs for every JS can be assigned by means of available JT cost templates as specified in Chapter 4.6.4.

After this, ascertainment of the JS Coefficient will require information on the complexity level of every single JS.

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Alu. - Alu.			Alu.-High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	Joining Tech. / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	0,005836	0,01642	1,25	--	--	--	0,006976	0,01613	1,50	--	--	--	0,00531	0,01137	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,05829	0,12421	1,50	--	--	--	0,04587	0,09774	1,25
3.	MIG welding	--	--	--	0,00685	0,01856	1,25	--	--	--	0,006659	0,019712	1,00	--	--	--	0,006274	0,016476	1,25
4.	Tandem MIG welding	--	--	--	0,00484	0,016917	1,25	--	--	--	0,005516	0,018699	1,25	--	--	--	0,004502	0,0156	1,25
5.	MAG welding	--	--	--	0,006792	0,01737	1,00	--	--	--	0,00794	0,02083	1,00	--	--	--	0,007307	0,01965	1,00
6.	WIG welding	--	--	--	0,00866	0,04032	1,00	--	--	--	--	--	--	--	--	--	0,008218	0,03844	1,00
7.	Laser-welding (CO_2)	--	--	--	0,01519	0,02449	1,25	--	--	--	0,01488	0,02556	1,25	--	--	--	0,01459	0,02316	1,25
8.	Laser-welding (Diodes)	--	--	--	0,016882	0,03954	1,25	--	--	--	0,01594	0,033729	1,25	--	--	--	0,01523	0,03154	1,25
9.	Laser-welding (YAG)	--	--	--	0,010221	0,020616	1,00	--	--	--	0,01233	0,02837	1,00	--	--	--	0,008105	0,016757	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,006782	0,01348	1,50	--	--	--	0,006545	0,01201	1,25
11.	Laser brazing	0,02075	0,029	1,00	--	--	--	0,02131	0,03001	1,25	--	--	--	0,02075	0,029	1,25	0,02047	0,02832	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,00646	0,02318	1,00
13.	Punch riveting	0,007994	0,03404	1,00	0,008115	0,033119	1,25	0,008467	0,039309	1,50	--	--	--	0,007994	0,03404	1,25	0,007876	0,03111	1,50
14.	Blind riveting	0,012012	0,035149	1,25	0,011147	0,031757	1,25	0,011756	0,034933	1,50	0,012489	0,036898	1,00	0,012012	0,035149	1,25	0,011147	0,031415	1,50
15.	Clinching	0,007717	0,021122	1,25	0,006512	0,016561	1,25	0,008323	0,024659	1,50	--	--	--	0,007717	0,021122	1,50	0,006712	0,01786	1,50
16.	Flanging	0,019123	0,030913	1,00	0,018764	0,029638	1,25	0,020562	0,034204	1,50	0,020926	0,034294	1,25	0,019123	0,030913	1,25	0,018405	0,029021	1,00
17.	Cohesiveness gluing	0,0125411	0,02915	1,25	0,012541	0,031107	1,25	0,011845	0,029164	1,25	0,011845	0,027348	1,25	0,0125411	0,02915	1,00	0,011147	0,023593	1,50

Table 6.4: Source Matrix with corresponding investment, manufacturing cost and JS Coefficient.

For this purpose the design department applies the Complexity Sheets for every JS and appraises the JS contour with its characteristics listed in the corresponding sheet. The appraised JSC's are added to the Source Matrix for the respective JT authorised for the JS analysed.

When the Source Matrix of the Industrial Case Study is filled, step two of the JT Selection Procedure has been completed. The Source Matrix, elaborated in Table 6.4, is used for the cost and SWC's calculation of the conventional and optimised JTSM within the Industrial Case Study. Required tables of the calculation steps are also listed in large print in the appendix G of the research work.

6.2.2.1 Calculation of Costs and Standardised Working Contents by means of the conventional Joining Technique Selection Procedure

In the course of the selection procedure of the Industrial Case Study, attention has been given to finding a suitable example where the conventional JT Selections have already been carried out by the company. Likewise the cost of the wheelhouse design concept has already been calculated by the finance department. This procedure provides an opportunity of direct comparison and appraisal of results obtained on the basis of both the conventional and the optimised solution.

JS number	1	2	3	4	5	6
Allocated JT number	13	3	11	5	13	1
Allocated JT	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding

Table 6.5: Conventional JT Selection solution of the Industrial Case Study.

The JT sequence (JT Solution Vector) of the conventional JT Selection solution of the design concept contained in the Industrial Case Study is adopted from the design department. It can be represented as a JT Solution Vector [13, 3, 11, 5, 13, 1] or as tabular, see Table 6.5.

The JT selection is determined by Design; subsequently, the production line concept is elaborated by Planning. Finally the cost is calculated with standard tools by Finance.

The JT combination proposed is marked in the Source Matrix of Table 6.6, the numerical values being taken from that of Table 6.4 and multiplied by the number of WC's in the corresponding JS and in the JSC elaborated.

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Aluminium - Aluminium			Alu. - High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	JT's / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	0,06566	0,18473	1,25	--	--	--	0,05232	0,12098	1,50	--	--	--	**0,03319**	**0,07106**	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,43718	0,93158	1,50	--	--	--	0,28669	0,61088	1,25
3.	MIG welding	--	--	--	**0,07706**	**0,20880**	1,25	--	--	--	0,03325	0,09856	1,00	--	--	--	0,03921	0,10298	1,25
4.	Tandem MIG welding	--	--	--	0,05445	0,19032	1,25	--	--	--	0,03448	0,11687	1,25	--	--	--	0,02814	0,09750	1,25
5.	MAG welding	--	--	--	0,06113	0,15633	1,00	--	--	--	**0,03970**	**0,10415**	1,00	--	--	--	0,03654	0,09825	1,00
6.	WIG welding	--	--	--	0,07794	0,36288	1,00	--	--	--	--	--	--	--	--	--	0,04109	0,19220	1,00
7.	Laser-welding (CO_2)	--	--	--	0,17089	0,27551	1,25	--	--	--	0,09300	0,15975	1,25	--	--	--	0,09119	0,14475	1,25
8.	Laser-welding (Diodes)	--	--	--	0,18992	0,44483	1,25	--	--	--	0,09963	0,21081	1,25	--	--	--	0,09519	0,19713	1,25
9.	Laser-welding (YAG)	--	--	--	0,09199	0,18554	1,00	--	--	--	0,06165	0,14185	1,00	--	--	--	0,04053	0,08379	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,05087	0,10110	1,50	--	--	--	0,04091	0,07506	1,25
11.	Laser brazing	0,08300	0,11600	1,00	--	--	--	**0,15983**	**0,22508**	1,25	--	--	--	0,08300	0,11600	1,00	0,12794	0,17700	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,03230	0,11590	1,00
13.	Punch riveting	**0,03198**	**0,13616**	1,00	0,09129	0,37259	1,25	0,07620	0,35378	1,50	--	--	--	**0,03997**	**0,17020**	1,25	0,05907	0,23333	1,50
14.	Blind riveting	0,06006	0,17575	1,25	0,12540	0,35727	1,25	0,10580	0,31440	1,50	0,06245	0,18449	1,00	0,06006	0,17575	1,25	0,08360	0,23561	1,50
15.	Clinching	0,03859	0,10561	1,25	0,07326	0,18631	1,25	0,07491	0,22193	1,50	--	--	--	0,04630	0,12673	1,50	0,05034	0,13395	1,50
16.	Flanging	0,07649	0,12365	1,00	0,21110	0,33343	1,25	0,18506	0,30784	1,50	0,13079	0,21434	1,25	0,09562	0,15457	1,25	0,09203	0,14511	1,00
17.	Cohesiveness gluing	0,06271	0,14575	1,25	0,14109	0,34995	1,25	0,08884	0,21873	1,25	0,07403	0,17093	1,25	0,05016	0,11660	1,00	0,06967	0,14746	1,25

Table 6.6: Source Matrix with conventional JT allocations for the Case Study.

In this manner the itemised investment and manufacturing costs per JS of the BIW wheelhouse become ascertainable, see Table 6.7 (Appendix Table 8.1.2). These are the single costs for the joining process of one BIW wheelhouse; if summed up, they give the total investment and manufacturing cost of one wheelhouse. This serves the purpose of generating a reference parameter for later comparison between the conventional and optimal solution.

Conventional Solution		1. Joining Side	2. Joining Side	3. Joining Side	4. Joining Side	5. Joining Side	6. Joining Side	Total cost per wheelhouse
Proposal Vector:	[13, 3,11, 5, 13,1]	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding	
Manufacturing cost M per JS		0,13616	0,2088	0,22508	0,10415	0,1702	0,07106	0,91545
Investment cost c per JS		0,03198	0,07706	0,15983	0,0397	0,03997	0,03319	0,3817

Table 6.7: Solution table for manufacturing and investment cost of the conventional JT allocation.

In the following step the number of SWC's is ascertained by means of the SWCC. This number, once obtained, serves in the same way as a reference parameter for subsequent comparison of the conventional and optimal estimation of the BIW design concept. Table 6.8 (Appendix Table 8.1.2) contains the relevant data for the calculation of the total number of SWC's by application of the conventional JTSM.

JS number	1	2	3	4	5	6	Total number of SWC's
Ascertained JT Combination	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding	
JS Material Combination	Aluminium - Steel	Aluminium-Aluminium	Aluminium-High tensile steel	Steel-High tensile steel	Aluminium-Steel	Steel-Steel	
Number of WC's	4	9	6	5	4	5	
SWCC	2,52002	1,52338	3,07674	1,72482	2,52002	1	
JSC	1,00	1,25	1,25	1,00	1,25	1,25	
Number of SWC's	10,08008	17,138025	23,07555	8,6241	12,6001	6,25	77,77

Table 6.8: Solution table for total number of SWC's of the conventional JT allocation.

For this purpose the number of WC's of one JS is multiplied by the corresponding SWCC that follows from the JT and material combination as specified in section 4.6.1. Finally the previous calculated values are multiplied with the appropriate JSC from the Source matrix. The tables for the calculation procedure are presented in larger scale in Appendix 8.1.

Through this procedure the number of SWC's for one JS has been determined. The subsequent summing up of the itemised SWC's of every JS will then yield the total number of SWC's for the BIW wheelhouse design concept of the Industrial Case Study. Consequently the pertinent economical and technical data of the BIW design concept have been identified for subsequent comparison of the conventional and optimised results obtained.

6.2.2.2 Calculation of Costs and SWC's by means of optimal JT Allocation

The process by which investment costs, manufacturing costs and the number of SWC's are calculated must begin with a determination of the optimal JT combination for the BIW design concept selected to meet the boundary constraints. Once the optimal JT combination has been obtained from the DP area by means of the CBP procedure, optimal investment and manufacturing costs can be calculated. Similarly, when the JT Solution Vector has been determined, the total number of SWC's can be calculated. It represents an ideal reference value for comparison of competing design concepts.

Before the JTSM can be carried out, the boundaries must be identified. This involves processing generally valid data taken from the automotive industry.

In the Industrial Case Study it is assumed that the BIW wheelhouse is designed for a medium-sized vehicle of which 200,000 units per year will be manufactured. The average production cycle of a given car is around seven years. For the construction of the body shell line an approved investment budget with a maximum of 560,000 EUR is provided by the finance department. The outcome of these generally valid data shows the following constraint for the limited investment budget C per unit:

$$\begin{aligned} C := & \frac{\text{approved investment budget}}{\text{number of BIW units per year} \times \text{years of production}} \\ = & \frac{560{,}000\ \text{EUR}}{200{,}000\ \text{units} \times 7\ \text{years}} = \underline{\underline{0{,}40\ \text{EUR}}}\ \text{per unit} \end{aligned} \tag{6.1}$$

Once the boundary for the limited investment budget C is determined, the DP computing of the JTSM is elaborated. For this purpose the Industrial Case Study is computed by application of the DP forward procedure.

minimise

$$M(k_1, \ldots, k_6) := M_1(k_1) + \ldots + M_6(k_6) \tag{6.2}$$

so that

$$C := c_1 + \ldots + c_6 \leq 0{,}40\ \text{EUR} \tag{6.3}$$

with the recursive equations:

$$f_1(x_1) := \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \{ M_1 (k_1) \} \qquad (5.13)$$

$$f_j(x_j) := \min_{\substack{\text{for all} \\ \text{feasible } k_j}} \{ M_j (k_j) + f_{j-1}(x_{j-1}) \} \qquad \text{with:} \quad j = 2,3, \ldots, 6 \qquad (5.14)$$

In the following, all values within the JTSM computation steps are increased by the factor 100 in order to simplify calculations for 100 BIW units. This is due to the fact that the calculation is carried out by hand. Once the DP computing has been effected, the JTSM is continued with the singular value consideration of one BIW unit.

Likewise in the previous conventional JT Selection Procedure the values within the Source Matrix have been multiplied by the corresponding WC's of the respective JS and the elaborated JSC. The resultant Source Matrix is represented in Table 6.9.

The values of the source matrix are taken as a basis for the DP computation according to the Capital Budgeting procedure. The identified six JS's of the BIW wheelhouse require six stages within the computation algorithm.

In the following description of the computation procedure the only stages indicated are the first two and the last, these being quite sufficient. The complete procedure is given in Appendix 8.2.

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Alu. - Alu.			Alu.-High tensile steel			Steel-High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	**Joining Tech. / Costs**	**c_1 [€]**	**M_1 [€]**		**c_2 [€]**	**M_2 [€]**		**c_3 [€]**	**M_3 [€]**		**c_4 [€]**	**M_4 [€]**		**c_5 [€]**	**M_5 [€]**		**c_6 [€]**	**M_6 [€]**	
1.	Spot welding	--	--	--	6,56550	18,47250	1,25	--	--	--	5,23200	12,09750	1,50	--	--	--	3,31875	7,10625	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	43,71750	93,15750	1,50	--	--	--	28,66875	61,08750	1,25
3.	MIG welding	--	--	--	7,70625	20,88000	1,25	--	--	--	3,32500	9,85600	1,00	--	--	--	3,92125	10,29750	1,25
4.	Tandem MIG welding	--	--	--	5,44500	19,03163	1,25	--	--	--	3,44750	11,68688	1,25	--	--	--	2,81375	9,75000	1,25
5.	MAG welding	--	--	--	6,11280	15,63300	1,00	--	--	--	3,97000	10,41500	1,00	--	--	--	3,65350	9,82500	1,00
6.	WIG welding	--	--	--	7,79400	36,28800	1,00	--	--	--	--	--	--	--	--	--	4,10900	19,22000	1,00
7.	Laser-welding (CO_2)	--	--	--	17,08875	27,55125	1,25	--	--	--	9,30000	15,97500	1,25	--	--	--	9,11875	14,47500	1,25
8.	Laser-welding (Diodes)	--	--	--	18,99225	44,48250	1,25	--	--	--	9,96250	21,08063	1,25	--	--	--	9,51875	19,71250	1,25
9.	Laser-welding (YAG)	--	--	--	9,19890	18,55440	1,00	--	--	--	6,16500	14,18500	1,00	--	--	--	4,05250	8,37850	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	5,08650	10,11000	1,50	--	--	--	4,09063	7,50625	1,25
11.	Laser brazing	8,30000	11,60000	1,00	--	--	--	15,98250	22,50750	1,25	--	--	--	8,30000	11,60000	1,00	12,79375	17,70000	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,23000	11,59000	1,00
13.	Punch riveting	3,19760	13,61600	1,00	9,12938	37,25888	1,25	7,62030	35,37810	1,50	--	--	--	3,99700	17,02000	1,25	5,90700	23,33250	1,50
14.	Blind riveting	6,00600	17,57450	1,25	12,54038	35,72663	1,25	10,58040	31,43970	1,50	6,24450	18,44900	1,00	6,00600	17,57450	1,25	8,36025	23,56125	1,50
15.	Clinching	3,85850	10,56100	1,25	7,32600	18,63113	1,25	7,49070	22,19310	1,50	--	--	--	4,63020	12,67320	1,50	5,03400	13,39500	1,50
16.	Flanging	7,64920	12,36520	1,00	21,10950	33,34275	1,25	18,50580	30,78360	1,50	13,07875	21,43375	1,25	9,56150	15,45650	1,25	9,20250	14,51050	1,00
17.	Cohesiveness gluing	6,27055	14,57500	1,25	14,10863	34,99538	1,25	8,88375	21,87300	1,25	7,40313	17,09250	1,25	5,01644	11,66000	1,00	6,96688	14,74563	1,25

Table 6.9: Source Matrix of the optimal JT allocation procedure for the Case Study.

Starting with stage 1 the authorised JT's (k_1=11, k_1=13, k_1=14, k_1=15, k_1=16, k_1=17) for JS1 with the corresponding manufacturing cost are listed. In compliance with the preassigned constraint that the investment budget C of 100 BIW wheelhouse units not exceed the amount of $x_1 \leq 40$ EUR, the optimal value for the stage 1 manufacturing cost is computed. By application of recursive equation (5.13) the optimal solution for stage 1 is appraised and the proposal vector for the proposal JT [15] is determined as indicated in Table 6.10.

$$f_1(x_1) = \min \{M_1(15)\} = 10{,}56 \text{ EUR} \qquad (6.4)$$

State 1	Manufacturing cost for feasible proposal : $M_1(k_1)$																	Optimal solution		
x1 [€]	$k_1=1$	$k_1=2$	$k_1=3$	$k_1=4$	$k_1=5$	$k_1=6$	$k_1=7$	$k_1=8$	$k_1=9$	$k_1=10$	$k_1=11$	$k_1=12$	$k_1=13$	$k_1=14$	$k_1=15$	$k_1=16$	$k_1=17$	$f_1(x_1)$	Proposal number	Proposal Vector
5											--		13,61	--	10,56	--	--	10,56	15	[15]
10											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
15											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
20											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
25											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
30											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
35											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
40											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]

Table 6.10: State1 of the DP computation by means of the Capital Budgeting Problem.

When stage 1 is completed, the algorithm of the CBP jumps to stage 2. Here again only authorised JT's (k_2's) for JS2 are accepted for the computation process. By the means of the recursive equation (5.14) of the CBP algorithm the minimum of the sum $\{M_2(k_2) + f_1(x_1)\}$ is computed.

$$\begin{aligned} f_2(x_2) &= \min \{M_2(k_2) + f_1(x_1)\} \qquad (6.5) \\ &= 15{,}63 \text{ EUR} + 10{,}56 \text{ EUR} = 26{,}19 \text{ EUR} \end{aligned}$$

with k_2 = 1, 3, 4, 5, 6, 7, 8, 9, 13, 14, 15,16, 17

$M_2(k_2)$: Manufacturing cost of JS2 under proposal k_2

$f_1(x_1)$: Optimal manufacturing cost of JS1

$f_2(x_2)$: Sum of optimal manufacturing cost for JS1 and JS2

State 2	Manufacturing cost for feasible proposals : $\{M_2(k_2) + f_1(x_2 - c_2(k_2))\}$										
x_2 [€]	$k_2 = 1$	$k_2 = 2$	$k_2 = 3$	$k_2 = 4$	$k_2 = 5$	$k_2 = 6$	$k_2 = 7$	$k_2 = 8$	$k_2 = 9$	$k_2 = 10$	$k_2 = 11$	$k_2 = 12$
10	18,47+13,61= 32,08 [13] 18,47+10,56=29,03 [15]		--	19,03+13,61=32,64 [13] 19,03+10,56=29,59 [15]	15,63+13,61=29,24 [13] 15,63+10,56=26,19 [15]	--	--	--	--			
15	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+14,57=50,85 [17]	--	--	18,55+13,61=32,16 [13] 18,55+10,56=29,11 [15]			
20	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	--	--	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
25	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
30	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
35	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
40	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			

Table 6.11: First part of Table 6.11: State 2 of the DP computing.

{M_2 (k_2) + f_1(x_2-c_2(k_2))}								Optimal solution		
k_2 = 10	k_2 = 11	k_2 = 12	k_2 = 13	k_2 = 14	k_2 = 15	k_2 = 16	k_2 = 17	$f_2(x_2)$	Proposal number	Proposal vector
			--	--	--	--	--	**26,19**	5	[15,5]
			37,25+13,61=50,86 [13] 37,25+10,56=47,81 [15]	--	18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	--	--	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	--	34,99+13,61=48,6 [13] 34,99+10,56=45,55 [15]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+13,61=46,95 [13] 33,34+10,56=43,9 [15]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]

Table 6.12: Second part of Table 6.11: State 2 of the DP computing.

State 6	Manufacturing cost for feasible proposals : $\{M_6(k_6) + f_5(x_6 - c_6(k_6))\}$																	Optimal solution		
x_6 [€]	$k_6 = 1$	$k_6 = 2$	$k_6 = 3$	$k_6 = 4$	$k_6 = 5$	$k_6 = 6$	$k_6 = 7$	$k_6 = 8$	$k_6 = 9$	$k_6 = 10$	$k_6 = 11$	$k_6 = 12$	$k_6 = 13$	$k_6 = 14$	$k_6 = 15$	$k_6 = 16$	$k_6 = 17$	$f_6(x_6)$	Proposal number	Proposal vector
35	7,10+70,58=77,68 [15,5,17,3,15]	--	10,29+70,58=80,87[15,5,17,3,15]	9,75+70,58=80,33 [15,5,17,3,15]	9,82+70,58=80,4 [15,5,17,3,15]	19,22+70,58=89,8 [15,5,17,3,15]	--	--	8,37+70,58=78,95 [15,5,17,3,15]	7,50+70,58=78,08 [15,5,17,3,15]	--	11,59+70,58=82,17 [15,5,17,3,15]	--	--	13,39+70,58=83,97 [15,5,17,3,15]	--	--	77,68	1	[15,5,17,3,15,1]
40	7,10+69,51=76,61 [15,5,17,3,11]	--	10,29+69,51=79,8 [15,5,17,3,11]	9,75+69,51=79,26 [15,5,17,3,11]	9,82+69,51=79,33 [15,5,17,3,11]	19,22+69,51=88,73 [15,5,17,3,11]	14,475+69,51=83,98 [15,5,17,3,11]	19,71+69,51=89,22 [15,5,17,3,11]	8,37+69,51=77,88 [15,5,17,3,11]	7,50+69,51=77,01 [15,5,17,3,11]	--	11,59+69,51=81,10 [15,5,17,3,11]	23,33+69,51=92,84 [15,5,17,3,11]	23,56+69,51=93,07 [15,5,17,3,11]	13,39+69,51=82,90 [15,5,17,3,11]	14,51+69,51=84,02 [15,5,17,3,11]	14,74+69,51=84,25 [15,5,17,3,11]	76,61	1	[15,5,17,3,11,1]

Table 6.13: State 6 with the optimal JT Proposal Vector of the Case Study.

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Aluminium - Aluminium			Alu. - High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	**JT's / Costs**	**c_1 [€]**	**M_1 [€]**		**c_2 [€]**	**M_2 [€]**		**c_3 [€]**	**M_3 [€]**		**c_4 [€]**	**M_4 [€]**		**c_5 [€]**	**M_5 [€]**		**c_6 [€]**	**M_6 [€]**	
1.	Spot welding	--	--	--	0,06566	0,18473	1,25	--	--	--	0,05232	0,12098	1,50	--	--	--	**0,03319**	**0,07106**	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,43718	0,93158	1,50	--	--	--	0,28669	0,61088	1,25
3.	MIG welding	--	--	--	0,07706	0,20880	1,25	--	--	--	**0,03325**	**0,09856**	1,00	--	--	--	0,03921	0,10298	1,25
4.	Tandem MIG welding	--	--	--	0,05445	0,19032	1,25	--	--	--	0,03448	0,11687	1,25	--	--	--	0,02814	0,09750	1,25
5.	MAG welding	--	--	--	**0,06113**	**0,15633**	1,00	--	--	--	0,03970	0,10415	1,00	--	--	--	0,03654	0,09825	1,00
6.	WIG welding	--	--	--	0,07794	0,36288	1,00	--	--	--	--	--	--	--	--	--	0,04109	0,19220	1,00
7.	Laser-welding (CO_2)	--	--	--	0,17089	0,27551	1,25	--	--	--	0,09300	0,15975	1,25	--	--	--	0,09119	0,14475	1,25
8.	Laser-welding (Diodes)	--	--	--	0,18992	0,44483	1,25	--	--	--	0,09963	0,21081	1,25	--	--	--	0,09519	0,19713	1,25
9.	Laser-welding (YAG)	--	--	--	0,09199	0,18554	1,00	--	--	--	0,06165	0,14185	1,00	--	--	--	0,04053	0,08379	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,05087	0,10110	1,50	--	--	--	0,04091	0,07506	1,25
11.	Laser brazing	0,08300	0,11600	1,00	--	--	--	0,15983	0,22508	1,25	--	--	--	**0,08300**	**0,11600**	1,00	0,12794	0,17700	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,03230	0,11590	1,00
13.	Punch riveting	0,03198	0,13616	1,00	0,09129	0,37259	1,25	0,07620	0,35378	1,50	--	--	--	0,03997	0,17020	1,25	0,05907	0,23333	1,50
14.	Blind riveting	0,06006	0,17575	1,25	0,12540	0,35727	1,25	0,10580	0,31440	1,50	0,06245	0,18449	1,00	0,06006	0,17575	1,25	0,08360	0,23561	1,50
15.	Clinching	**0,03859**	**0,10561**	1,25	0,07326	0,18631	1,25	0,07491	0,22193	1,50	--	--	--	0,04630	0,12673	1,50	0,05034	0,13395	1,50
16.	Flanging	0,07649	0,12365	1,00	0,21110	0,33343	1,25	0,18506	0,30784	1,50	0,13079	0,21434	1,25	0,09562	0,15457	1,25	0,09203	0,14511	1,00
17.	Cohesiveness gluing	0,06271	0,14575	1,25	0,14109	0,34995	1,25	**0,08884**	**0,21873**	1,25	0,07403	0,17093	1,25	0,05016	0,11660	1,00	0,06967	0,14746	1,25

Table 6.14: Source Matrix with marked JT Solution Vector of the optimal JTSM.

The computed value $f_2(x_2)$ = 26,19 EUR is the sum of the optimal manufacturing cost of JS1 and JS2 for stage 2. The appropriate JT's are constituted in form of a proposal vector [15, 5], which determined JT number 15 (Clinching) for JS1 and JT number 5 (MAG welding) for JS2 as the optimal solution in compliance with the established boundaries. Steps of calculation and the proposal vector are precisely elaborated in Table 6.11.

The Capital Budgeting algorithm will be continued later on by application of recursive equation (5.14), and is completed if stage 6 is computed. The final result $f_6(x_6)$ of the DP computing procedure can be gathered from Table 6.14.

Likewise the optimal JT Solution Vector [15, 5, 17, 3, 11, 1] can be automatically ascertained from the stage 6 table. It is separately given below in Table 6.15.

JS number	1	2	3	4	5	6
JT Solution Vector	15	5	17	3	11	1
Optimal allocated JT's	Clinching	MAG welding	Cohesiveness gluing	MIG welding	Laser brazing	Spot welding

Table 6.15: Joining Technique Solution Vector.

Once the optimal JT combination is computed by the CBP algorithm, the procedure for the manufacturing and investment cost calculation can be carried out. For that purpose the Solution Vector is assigned to the Source Matrix, as illustrated in Table 6.14.

In the following the several marked manufacturing and investment costs of the optimal JT combination must be summed up. This process is accomplished in the Solution Table 6.16, which calculates the total manufacturing and investment cost per BIW wheelhouse.

Permissible solution for C ≤ 40		1. Joining Side	2. Joining Side	3. Joining Side	4. Joining Side	5. Joining Side	6. Joining Side	Total cost per wheelhouse
Proposal vector:	[15, 5,17, 3, 11,1]	Clinching	MAG welding	Cohesiveness gluing	MIG welding	Laser brazing	Spot welding	
Manufacturing cost M per JS		0,10561	0,15633	0,21873	0,09856	0,116	0,0710625	0,7661
Investment cost c per JS		0,03859	0,061128	0,0888375	0,03325	0,083	0,0331875	0,3377

Table 6.16: Solution table for investment and optimal manufacturing cost of the Case Study.

In a final step the total number of SWC's is determined. This parameter reflects the economical and technical effort and is consequently an appropriate means for the juxtaposition of equivalent BIW design concepts. Detailed steps of the SWC's calculation have already been described at the end of the previous conventional JT

Selection Procedure. The results of the calculation of the total number of SWC's for the optimal JT combination of the Industrial Case Study are displayed in the following Solution Table 6.17.

JS number	1	2	3	4	5	6	Total number of SWC's
Ascertained JT Combination	Clinching	MAG welding	Cohesiveness gluing	MIG welding	Laser brazing	Spot welding	
JS Material Combination	Aluminium - Steel	Aluminium-Aluminium	Aluminium-High tensile steel	Steel-High tensile steel	Aluminium-Steel	Steel-Steel	
Number of WC	4	9	6	5	4	5	
SWCC	1,72896	1,44856	2,45857	1,581	2,98261	1	
JSC	1,25	1,00	1,25	1,00	1,00	1,25	
Number of SWC's	8,6448	13,03704	18,439275	7,905	11,93044	6,25	66,21

Table 6.17: Solution table for total number of SWC's of the optimal JT allocation.

The findings and results of the DP computation procedure of the Industrial Case Study are analysed and discussed in the following sections.

6.2.3 Analysis and Discussion of the Results of the Calculation

In the industrial Case Study "BIW wheelhouse with five sheet components, five material combinations and six JS's" calculation of cost and SWC's made in both the conventional and the optimisation way have led to results that are now available. Comparison of the financial figures shows that the optimisation solution effects a definite cost reduction of approximately 15%.

This theory can be extended to manufacturing as well as to that of investment. If it is applied to the design concept of the whole car body, with a volume of investment cost for a common body shell line of about 100-150 million Euros, it would effect an enormous cost reduction. This result, as already mentioned, is based on generally valid data taken from the automotive industry and from statements made by Finance.

Paramter / JT allocation	Manufacturing cost [€] per unit	Investment cost [€] per unit	Total cost [€] per BIW unit	Total number of SWC's
Conventional	0,9155	0,3817	1,2972	77,77
Optimisation	0,7661	0,3377	1,1038	66,21

Table 6.18: Solution Table with final results of the Industrial Case Study.

Analysis shows that investment costs amount to about one-third of the total, manufacturing costs accounting for the other two-thirds. This percentage is a rule of thumb that has already been applied in the finance department for making a quick and rough cost estimate for a new BIW design concept. This general cost estimation rule validates the proportion and appropriateness of the JT cost templates developed and the cost estimation methodology with its calculated results.

Juxtaposition of the total number of SWC's arrived at by the JT selection procedure based on the conventional method with the total number arrived at by the optimisation method yields the same 15% variance. This correlation is dispositional in the sense that the SWC's and also the manufacturing and investment costs are originally derived from the cycle time. The proportionality between the SWC's and costs is an enormous benefit of the application of WC's in the design departments. The designer can evaluate equivalent design concepts by means of the number of SWC's. A detailed description of the validation is explicated in the following section.

6.3 Validation of the Cost Estimating Methodology

Development of the optimal JT Selection Procedure in Chapter 5 has led to some primary results, of which the Industrial Case Study is largely an expansion. These consolidated findings corroborate that the JTSM is functional and practicable for design departments concerned with BIW in the automotive industry. As a result of the JTSM, compliance with the steps prescribed in the methodology is an absolute requirement if proper results are to be obtained. These steps have been elaborated and validated in collaboration with Design, Planning and Finance.

The research methodology was applied and tested by the researcher in the previous Industrial Case Study and is now to be evaluated against certain criteria. Hence, the highly scrutinised technical and economical contents of the main steps and their sub steps are validated by the improved results they lead to. Assumed boundaries are verified and new boundaries are acquired as a consequence of the improved procedures. In the same way assumed and new opportunities are verified. Finally, the evaluation of the total research validity is deduced by means of internal and external validation.

6.3.1 Applicability of the Research Methodology

The calculation and results of the methodology having been assessed as a comprehensive achievement by the design, planning and finance departments, the methodology itself is now to be evaluated by the criteria of feasibility, usefulness, and usability. All criteria are evaluated and validated by means of a second questionnaire with experts, see Appendix 10.

6.3.1.1 Feasibility

- The JTSM was successfully applied in the design, planning and finance departments with the researcher intervening to facilitate application of the methodology, see section 6.2.2.
- The questionnaire, accomplished in the above mentioned departments give the feasibility level of the JTSM for a new BIW design concept in middle to a 85% rating, see Appendix 10, question 6.
- The breakdown by departments of feasibility rating shown by the questionnaire is as follows, see Appendix 10, question 6.
    - Design department: 88.7%
    - Planning department: 85.4%
    - Finance department: 76.2%

6.3.1.2 Usefulness

- The methodology was considered useful for further calculations of BIW design concepts. Through the use of the methodology, the calculations identified an optimal solution and improved the conventional JT selection process, see section 6.2.2.
- Analysis of the questionnaire shows that the design, planning and finance departments give the usefulness a rating up to 90%, Appendix 10, question 7.
- The breakdown by departments of the usefulness rating shown by the questionnaire is as follows, see Appendix, question 7.
    - Design department: 85.6%
    - Planning department: 90.3%
    - Finance department: 74.5%

6.3.1.3 User-Friendliness

- The participants who had used the methodology argued that the quantity and complexity of the data and tabulations were difficult to handle.

- The questionnaire shows that Design, Planning and Finance give the user-friendliness of the JTSM a rating up to 76%, see Appendix 10, question 8.
- The breakdown by departments of the user-friendliness rating shown by the questionnaire is as follows, see Appendix 10, question 8.
  - Design department: 76.3%
  - Planning department: 71.4%
  - Finance department: 65.7%

The quantity and complexity of the data can be managed by a customised software tool.

6.3.2 Boundaries and Opportunities of the Calculation Process

6.3.2.1 Boundaries and Opportunities of the JTSM concerning the Calculation Process

Boundaries:

- The required cost data and cycle times used are based on generally valid data from the automotive industry, for example, that production of a series covers a range of seven years. Approximate 200,000 BIW units are manufactured per year in two shifts per day. Each shift takes 465 minutes and the man-year has 244 days. Analysed JTSP's have to be located within this range if proper absolute results for costs are to be achieved. If the JTSP is out of range, then the JT cost templates have to be adapted, a measure that demands additional labour time. A customised software tool can easily govern and quickly adapt the JT cost templates.

Opportunities:

- No constraints are placed on the number of JT's and JS's that may be demanded by the optimising JT Selection procedure. Hence, design concepts with a small or great number of sheet components can be calculated with the developed JTSM. This means that regardless of the direction in which the future trend of the BIW development process should go, the JTSM can be applied.
- Application of new materials and JT's, already specified in section 4.6.2, is no restriction for the accomplishment of the JTSM. It is simply a question of keeping the matrix of approved JT's and material combinations aligned.

- An update of investment and manufacturing cost within the JT cost templates can be conducted by the finance department without great effort. Hence the monetary values of the JTSM are always kept up to date with the result that results calculated and the strength of argumentation continue to enjoy a high degree of acceptance.
- The calculation of design concepts with conventionally determined JT's can be accomplished at any time and used for comparison with the optimising JT Selection Solution. This fact provides the designer with a broad scope of development within which to compute his favourite JT combination. JT's are determined both conventionally and by the optimising method. This means that the designer allocates particular JT's to defined JS's and determines the remaining JT's by means of the JTSM.
- The application area of the methodology can be expanded into the area of maintenance, energy and running cost or can find the optimum in terms of reliability of the JT's.

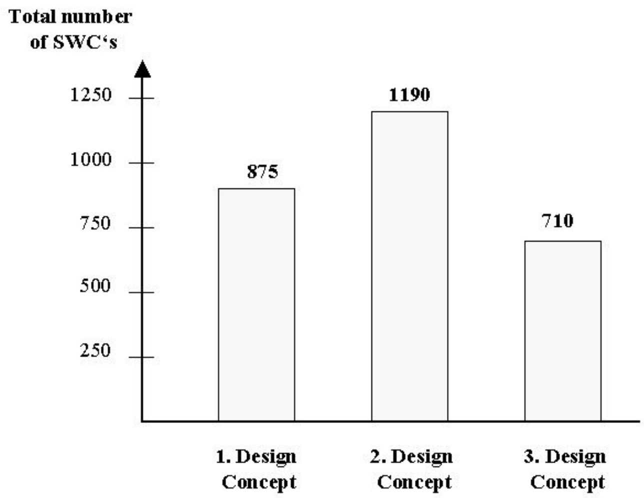
6.3.2.2 Boundaries and Opportunities of the SWC's concerning the Calculation Process

Boundaries:

- SWC's are based similarly on generally valid data as already explained in the previous section. If these data are varied, the SWC table must be adapted. Again, as before, it can be solved by application of a customised software tool.

Opportunities:

- All preassigned opportunities of the JTSM are also appropriate for the calculation of SWC's.
- If the designer ascertains the total number of SWC's of several equivalent design concepts, the designer can calculate subsequently the percentage difference of these concepts, as indicated in Figure 6.2.



Compared Design Concepts	Percentage difference between Design Concepts
1 <=> 2	36,00%
1 <=> 3	23,23%
2 <=> 3	67,60%

Figure 6.2: Example of percentage difference between Design Concepts.

Because of the proportionality between the SWC's and costs described at the end of section 6.2.3, the designer has simultaneously calculated the percentage difference of investment, manufacturing and total cost of the itemised design concepts. This is depicted by the example illustrated by the Figure 6.2. If the percentage difference between design concept one and three is 23.23%, then the relative costs percentage between the design concepts are equal.

The great advantage arising from application of the SWC's is that it provides the design department with an opportunity to compare design concepts with each other without having to calculate the cost of both manufacturing and investment every time.

6.3.3 Evaluation of the Total Research Validity

Once development of the research methodology is complete and the Industrial Case Study has provided pertinent results for validation and improvement, it is essential to balance the validity of the total research process. In order to permit a sufficient degree of validation, the question of research validity is broken down into internal and external validity. For this purpose internal validation is that effected within the sponsoring organisation, and external validation is that effected by participation of four conferences and one panel discussion.

6.3.3.1 Internal Validation

The internal validation of the research methodology sub-divides into the following three cases.

1. Accomplishment of the research methodology in the Centre of Competence (CoC) of the BIW design and planning department, see section 6.2.2.
2. Lectures on the research methodology before BIW experts with presentation and subsequent questionnaire, see Appendix 9.
3. Face-to-face interviews with BIW experts with presentation and subsequent questionnaire, see Appendix 9 and Appendix 10.

Once the Industrial Case Study was completed, further examples of BIW design concepts were calculated by the methodology in the BIW design department. The results obtained emphasise the validity of the research methodology.

For the requirement of area-wide internal validation a presentation of the research methodology with outcomes and benefits was elaborated and given before BIW expert groups, Appendix 10. For this purpose different BMW plants involved in BIW planning and production were visited. Within this lecturing process there were discussions about the feasibility, usefulness and usability of the research methodology.

Subsequently experts were asked to fill out a detailed questionnaire, Appendix 10, and sent it back by inter-office mail. Additionally face-to-face interviews with experts were held, these too involving presentations and questionnaires.

Results of the questionnaires provided an evaluation of previously mentioned research aspects. The presentation and questionnaire are attached to Appendices 9 and 10.

The total internal validity of the research methodology seemed high. The main arguments for this assertion are 1) the number of lectures and interviews, and 2) the quality of the resulting discussions. The frequent exchange of opinions with experts lends substance to the assertion.

6.3.3.2 External Validation

The external validity achieved in this research project is not as high as theoretically possible. The main reason for this is to be seen in the commitment of secrecy. Because of the data confidentiality, the sponsoring company could permit only restricted cooperation with competing automotive companies. Considerations of time and money precluded co-operation with companies involved in forms of production comparable to that of BIW, like shipbuilding, aircraft and railway construction. In the area of external validation the researcher participated in four conferences and one panel discussion. Each such event led to a publication containing the presentations and accompanying discussions on the research methodology. By means of these scholarly discussions held in public, the exchange of ideas with experts was seen to be an effective approach to evaluation of the research methodology. This outcome is taken to justify the assumption that the total external validity of the research methodology is high.

6.4 Summary

In the previous chapter calculations in an Industrial Case Study taken from the Body-in-White area of an automotive company were carried out by means of the cost estimation methodology. For this purpose the reader is introduced to a significant Industrial Case Study of a Body-in-White wheelhouse design with its material combinations and joining cycle. The design concept is the basis for the following conventional and optimising Joining Technique selection and computation process. First of all, the calculation of cost and of standardised Working Contents is conducted by means of the conventional Joining Technique selection procedure; the results thus obtained prove suitable for subsequent comparison with those obtained by means of the optimising Joining Technique selection procedure. For this purpose recourse is had to the *Capital Budgeting Problem* taken from the area of Dynamic Programming. Subsequently, after analysis and discussion of the results obtained in terms of cost and of standardised Working Contents, the validity of the Research Methodology is demonstrated. The research methodology was evaluated against the criteria of feasibility, usefulness and user-friendliness. Accordingly, while assumed and acquired boundaries and opportunities of the Joining Technique selection methodology and standardised Working Contents calculation are verified. Finally, the evaluation of the Total Research validity was achieved by means of internal and external validation.

7 Discussion, Conclusions and further Research

This chapter discusses the findings of the research and its technical and economic value to the automotive industry. Additionally the contribution to knowledge and the main conclusions of the research are outlined. Subsequently, the limitations of the method are pointed out. Finally this chapter and the thesis end with suggestions for further research opportunities.

The overriding reason or purpose for this research was to provide manufacturing cost estimation to Body-in-White designers that will enable them to make informed Body-in-White design choices in the preliminary work phase. This research developed a cost based methodology for optimal Body-in-White Joining Technology selection in the Early Phase of the automotive Product Development Process. This new methodology makes it possible for the Body-in-White designer to estimate manufacturing cost and to compare different new design concepts systematically.

7.1 Discussion

The major driver for the research project was the fact that the automotive Body-in-White designer does not have a method enabling him to estimate and compare the manufacturing costs of different new Body-in-White design options in the preliminary work phase of product development. This was the problem that gave rise to the research. The first step was to formulate a research aim, from which a working hypothesis and research objectives were derived as shown in section 1.3. These provided the essential guidelines of the research. The literature review in Chapter 2 investigates the importance of cost management in the automotive design process, showing that early cost estimation is critical to the success of any company and that significant cost savings can result from the prevention of later changes in product design as shown in section 2.2 and Figure 2.1. It becomes clear that the greatest knowledge gap is located in the detail design and development phase, see section 2.2.1. This is the domain of the BIW designer. This context brings out the need for an early cost estimation methodology that supports early decision making by the BIW designer.

The analysis of a generic vehicle Product Development Process in section 2.3.1 leads to the result that the BIW development stage is incorporated into the preliminary work phase of the PDP, which includes the initial phase, the concept phase and the preparation phase, see Figure 2.3. On this basis the point at which BIW cost estimation becomes possible was identified, and the methodology was developed accordingly. The literature review revealed likewise the overall business drivers of the research project, see section 2.3.2, namely that customer demand for more fuel-efficient vehicles makes a reduction of car body weight necessary. Hence the use of light-weight materials and the selection of cost efficient Joining Technologies are unavoidable.

In section 2.3.3 a review and analysis of major Joining Techniques with their process description and application in automotive production are described. It became clear that choosing a cost effective Joining Technique is of critical importance. Furthermore it became apparent that there is a link between Joining Techniques and Working Contents, see section 2.3.2, which, being useful for the comparison of different Body-in-White design concepts, is integrated into the later process of research methodology development in Chapter 5.

As the literature review given in section 2.3.2 shows, new technological developments for car weight reduction led to an increase in manufacturing cost for which, at present, sufficient information is not available. Hence the BIW engineer has no methodology enabling him to make an effective cost comparison of various design concepts in the Early Phase of development. In addition to the overall business drivers, there is constant pressure to shorten product development time, forcing the designer to make quick and significant decisions concerning his BIW design concept in terms of cost and technical characteristics. BIW development belongs to the core competence of every automotive OEM. Due to the fact that the car body makes up the largest part of the vehicle in terms of mass, it accounts for a large part of product cost. Hence the contribution of the BIW to total car cost is enormous, see section 2.3.2, and is the main reason for the necessity of a cost estimation methodology for BIW development. In this connection collaboration between the design, planning and finance departments is of critical importance for early cost estimation. This is confirmed by the literature review, section 2.4.3, questionnaire one, section 4.3.3.2 (question 8) and interviews section 4.4.2.1 (question 1.c). Quick data exchange between these departments will reduce development time for the BIW design concept and therewith development cost. In section 2.4, interactions between Design, Planning and Finance involved in the Body-in-White engineering process were analysed and described as an information feedback loop. This loop shows how much development time is consumed by these departments in appraising new BIW concepts in terms of cost. By means of the concept of Working Contents the time required for information exchange was shortened, and the amount of cost information on Joining Techniques made available to the design department was increased, see Figure 2.5. Working contents contain both technical and financial information pertinent to new BIW design concepts, enabling both engineers and cost experts to communicate with ease and speed. As a result, cooperation between departments involved in the BIW design process was substantially intensified.

Further investigations of the literature pertinent to the area of cost effective designing in sections 2.5 and 2.6 identify already available cost estimation and calculation systems. Because of the fact that the BIW cost estimating methodology should be used in the Early Phase of the PDP, only qualitative methods of cost estimating can be adopted, see Figure 2.12. The consideration of state-of-the-art cost estimating techniques, see section 2.6, shows, therefore, that there is no "off-the-shelf" solution available for the BIW cost estimating problem. It was apparent that Activity Based Costing, Resource Based Costing and Neural Networks cannot be used during the earlier product phases of the PDP. Furthermore Neural Networks cannot easily cope with innovative developments, which in the case of BIW design are central. Parametric cost estimating methods are sometimes too simplistic to forecast cost and could provide a completely misleading result. An empirical scaling method based on historical data for a family of closely related products made of the same materials is a domain too narrow and restrictive to be applicable to BIW cost estimating. The case based reasoning method, which presupposes the similarity of products, is also not appropriate for BIW cost estimating, see section 2.6. The finding was that extracts of the relative cost method can be utilised to assist as a basic approach for methodology development. This method of cost effective designing is qualitative and can be applied at the beginning of the concept phase of the Product Development Process.

By means of the evaluation of the research strategy in Chapter 3, feasible types of research methodologies were scrutinised, see section 3.3.3. After the consideration of the field of research, it became apparent that survey research was the technique most appropriate for data gathering in this research project. Additionally, case study research was chosen for the later application and evaluation of the methodology developed. Subsequently, the data collection methods were introduced in section 3.4.1. Interviews, questionnaires and analysis of documents were identified as the most relevant data collection techniques and were applied in the overall research process.

Once the lack of a BIW cost estimating methodology in the Early Phase of PDP, and the need for one, had been ascertained in Chapter 2 and the proper research methodology had been determined in Chapter 3, an industrial survey was carried out in Chapter 4. The objective of this survey was data gathering for the later development of the BIW cost estimating methodology. The need for it was ascertained by means of the first questionnaire, see section 4.3. Simultaneously interviews, see section 4.4, were carried out to gain technical and economic data, which were utilised for the development of tables, templates and matrices in section 4.6. Internal documents and literature were subjected to analysis for the same purpose, see section 4.5. Subsequently a precise definition for the use and calculation of Working Contents was developed in section 4.6.1. On this basis a Standardised Working Content coefficient was developed, see section 4.6.1.1. It offers the possibility of calculating the total number of standardised Working Contents for a Body-in-White design concept and provides the design department for the first time with an opportunity to make a comparison of various design concepts. With the information and data from interviews and the simultaneous analysis of internal documents and literature on one hand and close collaboration with experts from Planning on the other, a matrix of approved Joining Techniques and material combinations was developed by the researcher, see section 4.6.2. This matrix contains the necessary information on material combinations and Joining Techniques approved for the Body-in-White joining process. It gives the BIW designer the chance to select the right Joining Technique for his BIW material combination. In the course of over half a year Complexity Sheets were elaborated by the researcher with experts from the planning and manufacturing departments, see section 4.6.3. These sheets reveal the interrelationship between the part contour of a joining part and the cycle time for the joining process. To compensate for cycle time variation, which affects the joining cost -

and hence cost estimating - a Joining Side Coefficient was developed by the researcher. Subsequently, in section 4.6.4, Joining Technique Cost Templates were elaborated by the researcher in close cooperation with the planning, finance and manufacturing department of the sponsoring company. Within this time consuming process all data for the calculation of the investment and manufacturing cost of every single Joining Technique were collected, analysed and allocated to the various templates, see Appendix 7. These newly developed Joining Technique Cost Templates enable members of the design, planning and finance departments to estimate the total investment and manufacturing cost per operational unit for each separate Joining Technique.

In Figure 4.4 a simplified Body-in-White design concept model was developed. It showed the interrelationship between Joining Parts and Joining Sides and ascertained the number of Joining Technique combinations. This interrelationship is required for the later development of the BIW cost estimating method. Subsequent investigations in this area identify the exponential increase in the number of possible Joining Technique combinations for every BIW design concept, see section 4.6.5. This newly discovered basic fact revealed the demand for the finding and application of an optimisation technique capable of locating out of the enormous number of Joining Technique combinations possible, the one with greatest cost efficiency, see section 5.3.

Since all the elements required for the development of the cost estimating methodology – table, sheets, matrices and templates - have now been worked out and brought together, the following Chapter 5 goes into the development of the methodology itself. As a first elementary step a cost model defining a basic modelling process is presented as a basis for development of the cost estimation model, see section 5.2.1 and Figure 5.1. In accordance with this process the central problem of selecting the appropriate Joining Technique is described in detail and formulated as a generic model, see section 5.2.3. Subsequently a corresponding algorithm, see Figure 5.2 and Figure 5.3, for allocation of Joining Technique to Joining Sides is elaborated. This algorithm shows how to find the most cost efficient Joining Technique for every Joining Side and provides a basis for identifying an appropriate allocation model taken from the area of Operations Research. In this context a Joining Technique - Joining Side matrix, see

Table 5.1, also called source matrix, which bundles the essential technical and financial data of one Body-in-White design concept into one central matrix, was developed by the researcher. This representation of all essential data into a matrix provides a foundation for the process of selecting the most cost efficient Joining Technique. The next step is to locate a suitable optimisation model in the area of Operations Research. Of all OR models analysed, see section 5.3, those best suited to the present research problem, which concerns methodology, are the prescriptive models, which actually select a policy. Of these the algorithmic ones (optimisation model) offer mathematical proof that they will work for a certain range of cases. Furthermore the problem of Joining Technique Selection is deterministic; based on a state of certainty, there can be no variability in the model's parameter, which therefore takes only a single value. For this reason the research problem belongs to the category of deterministic, algorithm models, see Figure 5.5. Within the deterministic category, Linear Programming with the Transportation Problem can be applied to the Joining Technique selection problem, see section 5.5.2. The objective of the aligned Transportation Problem was to optimise the Joining Technique selection in such a way as to minimise the total cost of manufacturing. However, while application of this algorithm turned out to be cost-saving, it was not cost-optimal, see section 5.5.2.2. Consequently, the research was further expanded in the area of Dynamic Programming, and here the Capital Budgeting Procedure was found most appropriate for the optimal Joining Technique selection problem, see section 5.6.3. The Capital Budgeting Procedure involves an allocation problem that can deal with the magnitude of possible Joining Technique combinations. Application of the Capital Budgeting Procedure to a first Joining Technique selection problem yielded proper optimal solutions, see Table 5.13 and Table 5.14. The complete cost estimating model is shown in section 5.8. This model comprises all pertinent information and results of the previous research. It is divided into three steps, all pertaining to data: analysing (Figure 5.9), gathering (Figure 5.10) and computing (Figure 5.11). Therewith the method provides a systematic approach to the estimating of the manufacturing cost of new BIW design concepts. Additionally the method provides the total number of standardised Working Contents of the design concept under scrutiny, so that the BIW designer can also make comparisons of different BIW design concepts. With this the aim of the research project with its hypothesis and objectives is accomplished because the new method provides the BIW designer with the option of selecting the most cost efficient Joining Technique combination and hence of comparing different new design concepts more systematically and more reliably in the Early Phase of the Product Development Process, see section 1.3.

For the evaluation of the new method with its results an industrial case study pertaining to a Body-in-White design concept was carried out in Chapter 6. For a subsequent comparison of results obtained the case study was carried out in two ways: first by means of the conventional calculation as shown in section 6.2.2.1, and second with the optimisation methodology in section 6.2.2.2. Analysis of the results achieved showed that the new cost estimation methodology substantially reduces the manufacturing cost of a given Body-in-White design concept. In the present case, as indicated in section 6.2.3, a definite cost reduction of approximately 15% was achieved. These results have been elaborated and validated in collaboration with the design, planning and finance office of the sponsoring company. In the final phase a validation of the overall research method was conducted by means of a questionnaire, see Appendix 10 and section 6.3. It confirmed the applicability of the estimation methodology in terms of feasibility, usefulness and user friendliness. Similarly, boundaries and opportunities of the calculation process were summarised and discussed, see section 6.3.2. On the basis of both internal validation, i.e. validation based on information internal to the sponsoring company, and external validation, i.e. validation based on information from competing companies, see section 6.3.3, it may be claimed that the overall research validity is high. But for restrictions on accessibility to the manufacturing data of competing companies, the external validation, might even have been higher. To compensate for these restrictions the researcher participated in four conferences and one panel discussion, see Appendix 1. Each such event, based on a publication containing a presentation of the research methodology, led to discussions confirming its validity. This outcome leads to the assumption that the total external validity of the research methodology is high.

7.2 Contributions to Knowledge

The contribution to knowledge is twofold: first of all there is an overall cost estimation methodology permitting comparison of various Body-in-White design concepts, see section 4.6.1.1, section 5.6.3 and section 5.8; the second, on the basis of which the first is developed, is a procedure for identifying the optimal Joining Technique combination in terms of manufacturing cost for each design considered, see section 5.6.3.1, Table 5.14, section 5.8 and section 6.2.2.2.

7.2.1 Primary Contribution

It has been shown that systematically manufacturing cost estimation of Body-in-White design concepts is possible in the Early Phase of the Product Development Process, see section 5.8 and section 6.2.2. This early cost estimation enables the Body-in-White designer to compare various new design concepts in terms of Standardised Working Contents and manufacturing cost, see section 6.2.3 and Figure 6.2. In this wise the cost assessment currently done by Finance in conjunction with Planning will be largely anticipated and expedited. The choice of a new BIW design concept will be accomplished in less time and with greater reliability, and will be attended with a significant savings in cost.

7.2.2 Secondary Contribution

A generic cost based Joining Technique selection procedure is developed with focus on the specific needs of the Body-in-White design engineers, see section 5.6.3 and section 5.8. This procedure can identify the optimal combination of Joining Techniques for a given Body-in-White design by means of computational techniques taken from Operations Research. This procedure is based on the concept of the standardised Working Content, see section 4.6.1.1, which serves as unit of measure. This arithmetical unit is an arbitrarily selected natural Joining Technique of which all others can be expressed as multiples. The concept of the Working Content, see section 4.6.1, 1.) provides the designer with a method for ascertaining systematically the relative costs of various design concepts, see section 5.8; 2.) facilitates early data exchange between the design, planning and finance departments, see section 2.4; and 3.) makes the choice of a new design concept economical, see section 6.2.3 and Figure 6.2. The Body-in-White design with the lowest number of standardised Work Contents is automatically a benchmark on which further developments can be oriented.

These outcomes will support design, planning and finance activities. Due to the fact that with this methodology early cost estimation and relevant data exchange are systematically possible, Planning and Finance can start their activities in the preliminary work phase, see section 2.3.2, section 2.4.1 to section 2.4.3. Hence, the reliability of the results can be increased since a larger time window is available for the following processes in the PDP. Discussions with BIW engineers conducted on the basis of Working Contents are more transparent. Furthermore Finance obtains "bite-sized" data from the early cost estimation already carried out by Design.

7.3 Conclusions

Section 1.3 defined the research aim, hypothesis and objectives. In order to measure the degree to which these objectives have been met, it will be necessary to compare them with the conclusions. So this section considers the stated research aim, hypothesis and objectives in terms of whether or not they are satisfied at the end of the research project.

7.3.1 Research Aim

The aim of this research is:
To develop a methodology that will enable Body-in-White designers (or managers) to compare the manufacturing costs of different new design concepts more systematically.
This aim has been achieved. An entire cost estimating method focussed on the specific needs of the Body-in-White design engineers and involving all pertinent information and results obtained by the methodology research work has been developed, see section 5.8, and validated in the industrial case study, see chapter 6. This model makes it possible for the user group to estimate accurately the manufacturing costs for different new design concepts, see section 6.2.2. The subsequent comparison of these different design concepts could be carried out on the basis of cost or of standardised Working Contents, see section 6.2.3 and Figure 6.2.

7.3.2 Research Hypothesis

The research hypothesis of this research is:

The research will proceed on the assumption is that it is possible to develop a methodology for estimating the relative manufacturing costs of different Body-in-White design concepts on the basis of information contained in the specification data of the new design concepts.

The assumption of the Research Hypothesis has been justified. From the design specification and the component drawings the following can be gathered: 1.) the combination of material components, see section 4.6.2; 2.) the level of their complexity, see section 4.6.3; and 3.) the number of Joining Sides and their length, see Figure 4.4 and section 6.2.2, 2.). These data are the most essential input for the methodology developed. These essential data are worked out in sections 4.6 and their application in sections 5.8 and section 6.2.2.

7.3.3 Research Objectives

The goal of this study was defined in the Research Objectives as follows:

The primary objective is to develop a procedure for identifying the optimal combination of Joining Techniques for a Body-in-White design concept.

A generic Joining Technique selection procedure has been designed on the basis of Dynamic Programming, which is taken from the area of Operations Research and is focussed on the specific needs of the Body-in-White design engineers, see section 5.6. This procedure, based on a previously developed series of data gathering techniques in section 4.6, is computational and provides a holistic method for arriving at a Joining Technique selection for the Body-in-White design concept under scrutiny that will be optimal in terms of manufacturing costs and compliance with technical and economic boundary conditions, section 5.8. The procedure thus developed constitutes the primary component of the overall methodology for estimating the manufacturing cost of a BIW design concept.

Accordingly the following sub-objectives were defined:

Sub-objective 1: *To develop a definition of the Body-in-White Working Content as the mathematical unit for the above mentioned procedure.*

The definition and use of the Working Content unit in the Early Phase of the design process is carried out in sections 4.6.1, 4.6.5, 2.3.2 and 2.4. The Working Content unit is primary mathematical parameter for the computation of the optimal Joining Technique combination. It will also facilitate data exchange between the design, planning and finance departments all of which are centrally involved in the design process, see section 2.4.1.

Sub-objective 2: *To establish a mathematically definable connection between Working Contents and Joining Techniques.*

This objective is realised in section.4.6.1, where, in Table 4.1, the pertinent coefficients are listed. The fundamental reasoning is that while a Working Content is a natural unit of work, e.g. the gluing of two Joining Sides 50 millimetres in length, the amount of work involved in every joining, in every natural unit of work, can be expressed as an integral or fractional multiple of the simplest and quickest of all, namely one spot weld of steel to steel, see section 4.6.1.1. This, therefore, is the standardised Working Content, the unit of work, the standard measure that permits an arithmetical treatment of all other Working Contents.

Sub-objective 3: *To collect raw data and put them into a form that will make them serviceable for the development of the methodology sought.*

The industrial survey collects, analyses and organises technical and economic data required for the development of the Joining Technique selection procedure and hence of the overall cost estimation methodology, see section 4.6. These data are contained in: the Standardised Working Content Coefficients table, see section 4.6.1.1, matrix of approved Joining Techniques and material combination, see section 4.6.2; Complexity Sheets, see section 4.6.3; Joining Technique cost templates, see section 4.6.4; and Joining Technique – Joining Side matrix, see section 5.2.4 and Table 5.1.

The research project has sufficiently fulfilled its aim, hypothesis and objectives. They were satisfied by the steps of the literature review, industrial survey, development of the cost estimating method and the carrying out of the industrial case study.

7.4 Limitations of the Method

The design and implementation of the research methodology is attended by some limitations that could affect results. The section begins with the field of application, continues with the application period and closes with the capability of estimated results to which the methodology leads.

7.4.1 Field of Application

An element of limitation concerns the scope of the research methodology. As mentioned in the introduction of the thesis, see section 1.3.4, the research scope is addressed to the OEM Body-in-White engineers of the automotive industry. For this purpose the boundaries of application for the developed and validated methodology are designed for the specific application range 100,000 – 200,000 BIW units per year over a production period of seven years. This range represents an average production cycle for a medium-sized vehicle. Cost estimation out of this range requires an adjustment of the technical and economic terms. The application of the methodology outside of the automotive industry with companies involved in forms of production comparable to that of BIW, like shipbuilding, aircraft and railway construction have not been carefully examined because of the time scope of the doctoral programme.

7.4.2 Application Period

Additionally to the application field, the period of application of the research methodology within the automotive Product Development Process is of critical importance. The developed estimation methodology provides proper results from the concept phase of the preliminary work phase of the automotive Product Development Process. From this phase, on through the series development phase, and continuing until the Start-of-Production of the Product Development Process phase, reliable cost estimation of a new Body-in-White design concept is feasible but not necessary because traditional cost calculation systems are available. Earlier cost estimation within the strategy and initial phase of the Product Development Process cannot be supported by the methodology because of the lack of consistent data in these phases.

7.4.3 Capability of the Estimated Results

Because of the lack of consistent data in the Early Phase of the Product Development Process, the estimation methodology cannot provide precise manufacturing cost results for new Body-in-White design concepts. This cannot be done until the data required for traditional cost calculation have become available. The methodology provides only relative cost estimates of Body-in-White design concepts. Such estimates are of use only at the concept phase of the Product Development Process and help in the choice of new design concepts. On the basis of the research aim, it is not of critical importance to calculate the exact future manufacturing cost; rather it is important to provide the Body-in-White designer with a good comparative estimate of manufacturing cost in the preliminary work phase.

The above mentioned limitations provide a framework for the applicability of the developed methodology. The context in which the estimation methodology provides its support is that of Body-in-White design. Some of the limitations of the research programme provide opportunities for future research considered in the following section.

7.5 Further Research

The work on BIW cost estimating is a complex and challenging research area, which leaves many interesting possibilities for future work. This section examines areas that require further research to improve application of the cost estimate methodology. It starts by a) outlining opportunities for enhancing the user-friendliness of the methodology, b) gives a direction to further testing, c) expand the field of application, d) expand the application period and e) improve the capability of the estimated results.

7.5.1 Opportunities for enhancing the cost estimation methodology

A further area for research would be to develop a customised software tool that combines all previously developed methods and data of the cost estimation methodology, see section 4.6 and section 5.8. This would automate the cost estimation process. On the basis of this requirement, several sub-methods could additionally be expanded.

- For the cost estimation process the research methodology requires certain technical and economic data tables, see section 4.6.2 to section 4.6.4 and Figure 5.10. Concern with accuracy requires that these data be continually updated; a tool could be developed to insure that they are.
- One fundamental stage of the estimation methodology requires the data transfer of the Joining Side properties from all Joining Sides of a calculated Body-in-White design concept into the basic source matrix, see Figure 5.10 and Table 6.4. A software tool connected to the interface of the CAD tool is needed to simplify the data transfer while preventing error. This tool would significantly shorten the processing time of the cost estimation procedure.
- During the development of the optimal Joining Technique selection, the Joining Side coefficient was incorporated into the methodology, see section 4.6.3. This coefficient has been ranked into three grades of weighting. Subsequent research would have to improve on the weighting coefficients for a more precise ascertainment of the complexity level of a given Joining Side. Such a continual improvement would increase the accuracy of the optimal Joining Technique selection finding.
- During the Industrial Case Study the Capital Budgeting Problem calculation process was calculated manually, see section 5.6.3.1 and section 6.2.2.2. A customised software tool would automate the calculation process and reduce the possibility of human error.

7.5.2 Opportunities for further testing

It is believed however, that the methodology can be enhanced further through more case studies researching. This would extend the generalisation and give added validity to the case research. Within the time available only a limited effort could be made to understand the long-term impact of the methodology, to evaluate the application of the entire methodology. Further evaluation will provide greater familiarity with the methodology and may lead to further refinement.

For this purpose additional testing of more complex Body-in-White design concepts, see Figure 6.1, with increased technical and economic interdependencies within the automotive industry would have to be carried out.

7.5.3 Expansion of the field of application

Further research would be necessary into the area of manufacturing processes comparable to that of Body-in-White, like shipbuilding, aircraft and railway construction. This stage could lead to the result that the cost-effective designing process could be tailored to each company's need.

Likewise the actual application range of 100,000 – 200,000 BIW units per year over a production period of seven years, which represents an average production cycle for a medium-sized vehicle, could be changed or varied. Cost estimation out of this range requires an adjustment of the Joining Technique Cost Templates and the Standardised Working Content Coefficient.

7.5.4 Expansion of the application period

The period of application of the BIW manufacturing cost estimating method starts with the concept phase of the preliminary work phase of the Product Development Process, see Figure 2.3, and can be retained until commencement of the Start-of-Production phase. Nowadays, earlier cost estimating is not possible because of the lack of consistent data in the Initial Phase of the Product Development process. If there are technological changes in the application of the current Product Development Process, and if data consistency is confirmed, then the question arises whether earlier cost estimating is possible. To decide this, the information contained in the specification data of the new BIW design concepts must be analysed to see whether there are data sufficient to satisfy the Source Matrix, see Figure 5.9, Figure 5.10 and Table 6.9 of the BIW cost estimating method.

This section has examined areas for further research and development that aim to apply the methodology to the Body-in-White designing section and to contribute to its realisation. Whenever a new methodology is implemented, changes in the way in which things are done become inevitable.

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Appendix

1. List of Publications

(1.) J. W. Stahl and W. Appold (2001):
Verlustkostenreduzierung, Opportunitätskostenanalyse unter TPM - Gesichtspunkten. Zeitschrift für Unternehmensentwicklung und Industrial Engineering, Heft 5/November 2001, 50. Jahrgang, ISSN 1431-2271, p.201-204.

(2.) J. W. Stahl, V. Vitanov and W. Appold (2003):
Decision Support System for the Early Phase of the Automotive Development Process. 1st International Conference on Manufacturing Research (ICMR 2003). Glasgow September 2003, p.217-222.

(3.) J. W. Stahl, V. Vitanov and M. Ganser (2004):
Optimisation of the Joining Process Selection in the Early Phase of the Automotive Development Process. 34th International MATADOR Conference. Manchester July 2004, ISBN 1-85233-880-6 Springer London Berlin Heidelberg.

(4.) V.Vitanov, J. W. Stahl, M. Ganser (2006):
Optimal Selection of the Joining Technology in the Automotive Development Process. 3rd Future Business Technology Conference (FUBUTEC 2006). Athens April 2006.

(5.) V.Vitanov, J. W. Stahl, M. Ganser (2006):
Optimal Joining Technology Selection for the Automotive Product Development Process. 3rd International Conference on Group Technology / Cellular Manufacturing (GTCM 2006). Groningen July 2006.

2. First Questionnaire

2.1 Questions

I. General Questions

Q1: What is your job title?

A1: A 1 = ______________________________

Q2: Which department you are working for?

A2:

Finance Department	Planning Department	Design Department
☐	☐	☐

Q3: For how many years have you been working in that field?

A3:

≥ 10 Years	≥ 8 Years	≥ 6 Years	≥ 4 Years	≥ 2 Years	≥ 1 Year
☐	☐	☐	☐	☐	☐

II. Specific Questions

Q4: Is it possible for your department to estimate manufacturing cost for a new Body-in-white design at the preliminary phase by using a appropriate method?

A4: ☐ Yes ☐ No

Q5: In which phase of the Product Development Process can you normally start with the cost estimation for a new design?

A5:

Initial Phase	Concept Phase	Preparation Phase	Coordination Phase	Confirmation Phase	Maturation Phase	Start of Production
☐	☐	☐	☐	☐	☐	☐

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Table 2.1.1: First Questionnaire, page 1.

Q6: If a new BIW design drawing is available, how long would it take to estimate the manufacturing costs?

A6:

≥ 24 weeks	≥ 20 weeks	≥ 16 weeks	≥ 12 weeks	≥ 8 weeks	≥ 4 weeks	≥ 2 weeks
☐	☐	☐	☐	☐	☐	☐

Q7: What source of data are available to you in order to proceed with the estimation? More than one answer is possible.

A7:

Design Department	Planning Department	Finance Department	Manufacturing Department
☐	☐	☐	☐

Q8: Which of the departments in Q7 provide data that is of critical importance for your cost estimate?
Could you please indicate on a scale from 0-100 the importance of data flows.

Less importance — high importance

0% — 25% — 50% — 75% — 100%

A8:

A 8.1 Finance Department = ... %
A 8.2 Planning Department = ... %
A 8.3 Design Department = ... %
A 8.4 Manufacturing Department = ... %

Q9: Could you indicate your confidence level into the obtained information using the scale below?

A9:

100%	90%	80%	70%	60%	50%	Less 50%
☐	☐	☐	☐	☐	☐	☐

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Table 2.1.2: First Questionnaire, page 2.

Q10: How long does it take to obtain the information from the data source?

A10:

≥32 Weeks	≥ 24 Weeks	≥ 16 Weeks	≥ 8 Weeks	≥ 4 Weeks	≥ 2 Weeks	≥ 1 Weeks
☐	☐	☐	☐	☐	☐	☐

Q11: Can you rank using a 100%-scale the importance to have a new tool in your working area for a rough manufacturing cost estimation at the Early Phase of the development process?

Less importance — high importance

0% — 25% — 50% — 75% — 100%

A11: A 11 = ... %

Q12: Do you expect that this new tool will have an impact on your decision making process?

No impact — Great impact

0% — 25% — 50% — 75% — 100%

A12: A 12 = ... %

-3-

Table 2.1.3: First Questionnaire, page 3.

2.2 Results of Specific Questions

Question 4: Is it possible for your department to estimate manufacturing cost for a new Body-in-white design concept at the preliminary phase by using a appropriate Method?

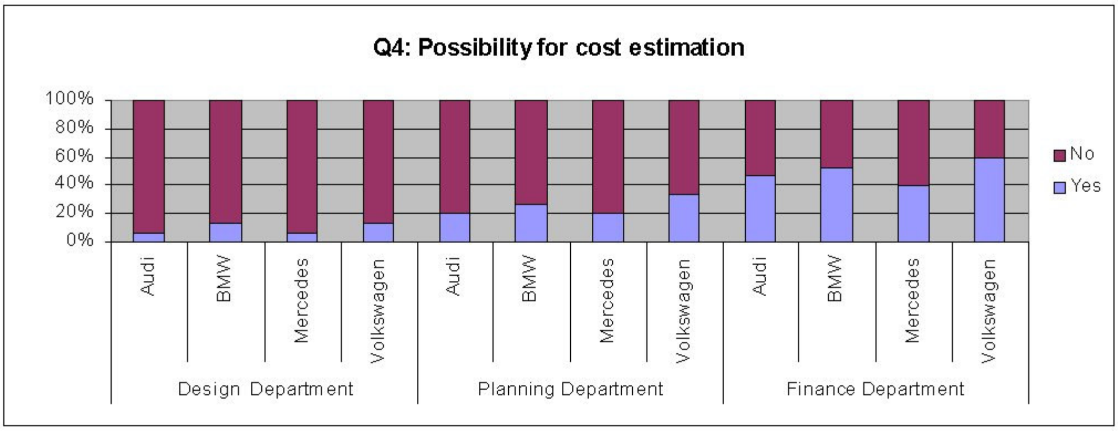


Table 2.2.1: Results of question 4.

Question 5: In which phase of the Product Development Process can you normally start the cost estimation for a new design?

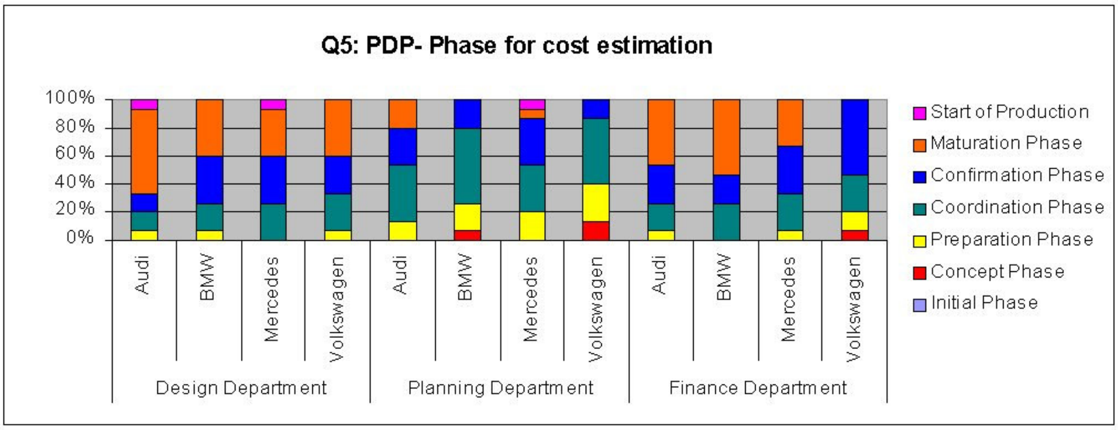


Table 2.2.2: Results of question 5.

Question 6: If a new BIW design drawing is available, how long would it take to estimate the manufacturing costs?

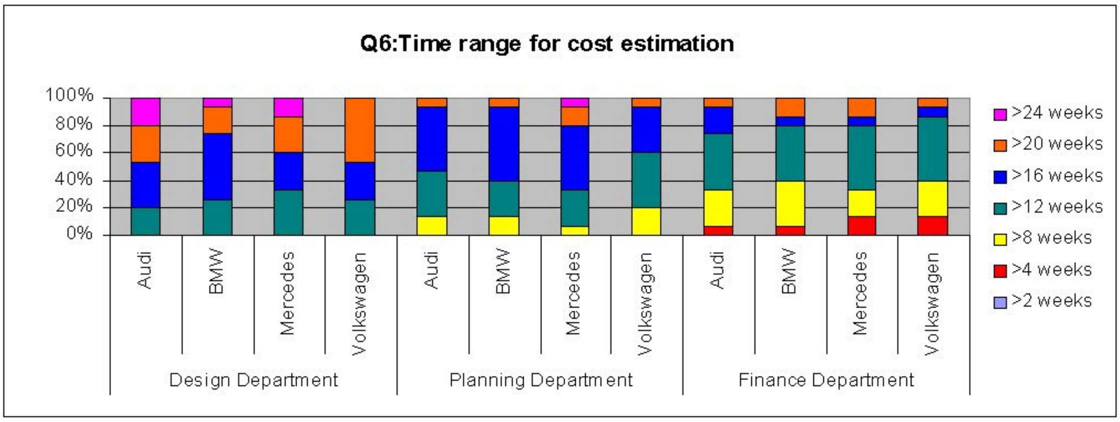


Table 2.2.3: Results of question 6.

Question 7: What source of data are available to you in order to proceed with the estimation?

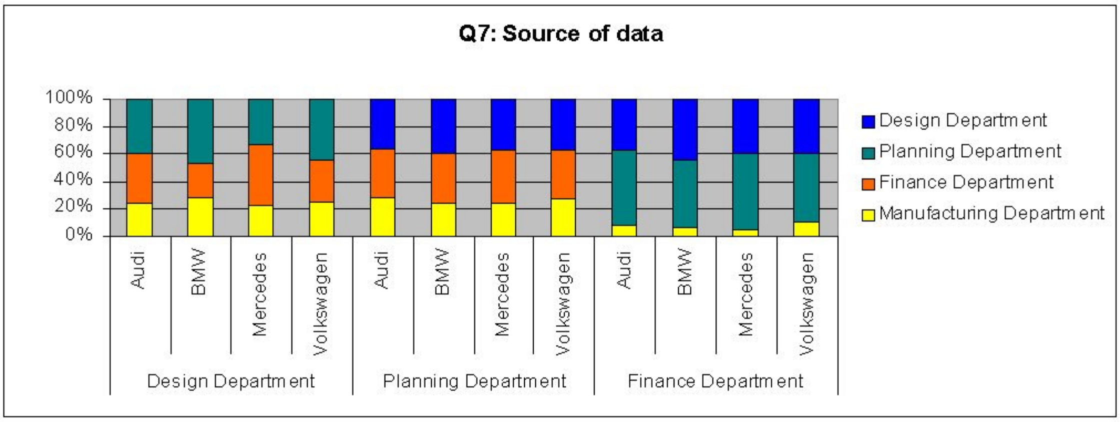


Table 2.2.4: Results of question 7.

Question 8: Which of the departments in Q7 provide data that is of critical importance for your cost estimate?

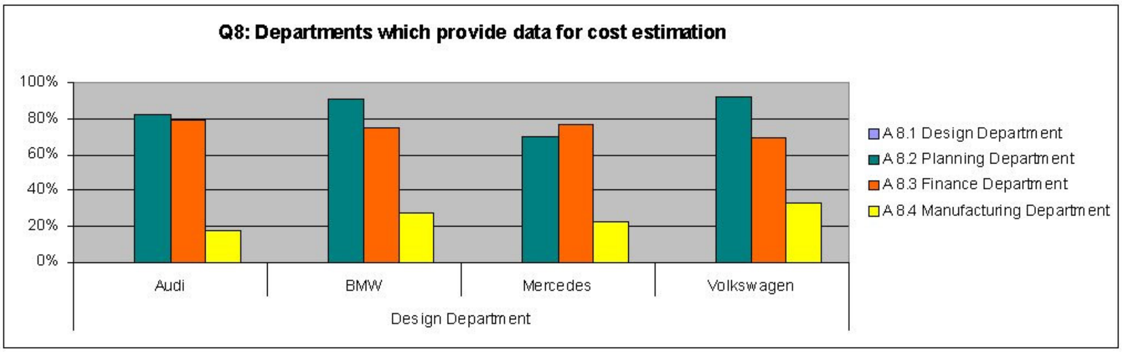


Table 2.2.5: Results of question 8.

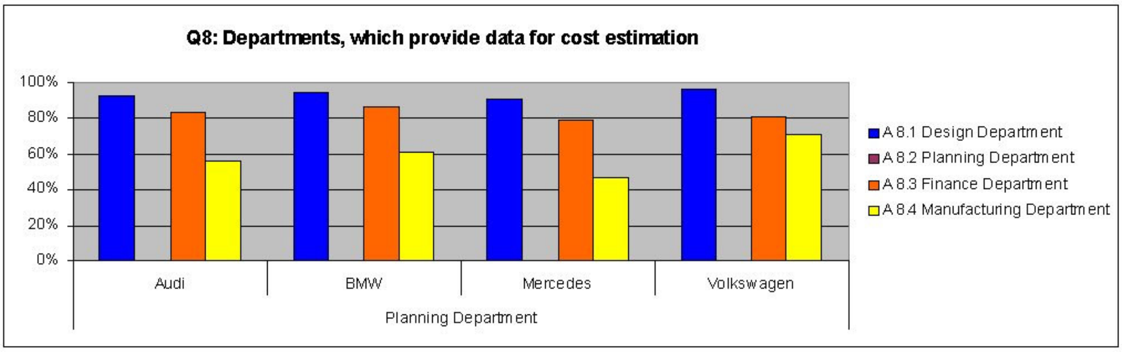


Table 2.2.6: Results of question 8.

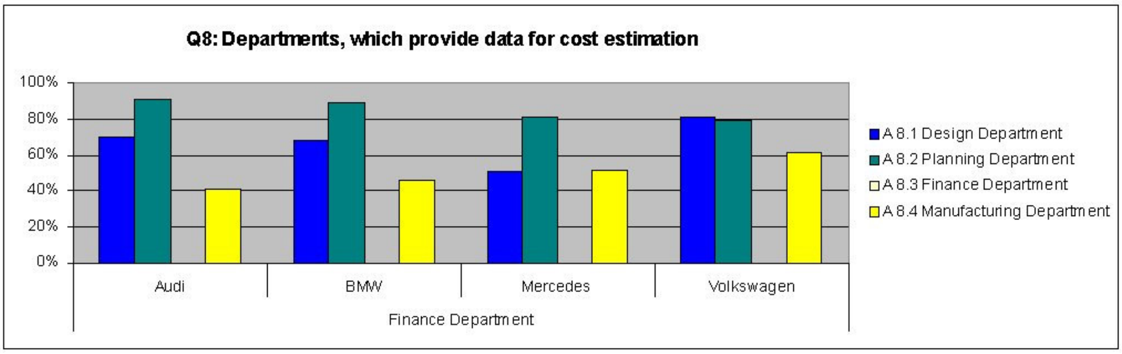


Table 2.2.7: Results of question 8.

Question 9: Could you indicate your confidence level into the obtained information using the scale below?

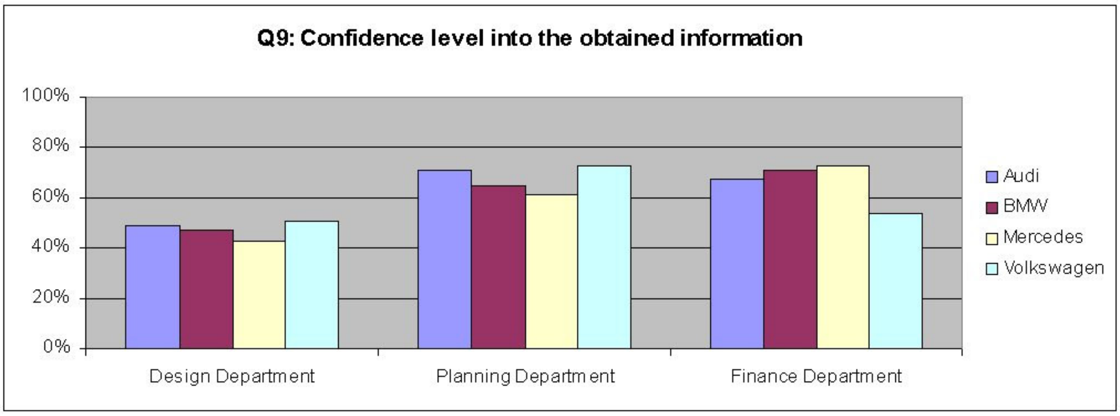


Table 2.2.8: Results of question 9.

Question 10: How long does it take to obtain the information from the data source?

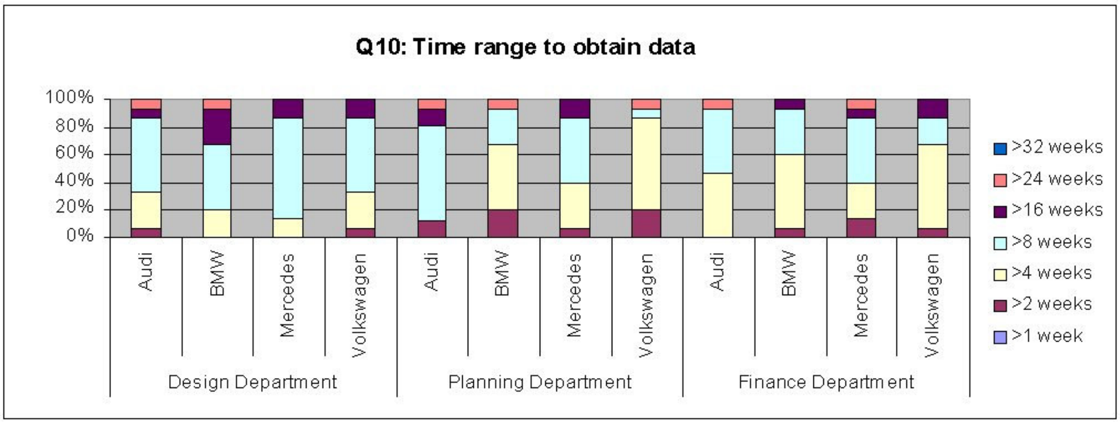


Table 2.2.9: Results of question 10.

Question 11: Can you rank using a 100%-scale the importance to have a new tool in your working area for a rough manufacturing cost estimation at the Early Phase of the development process?

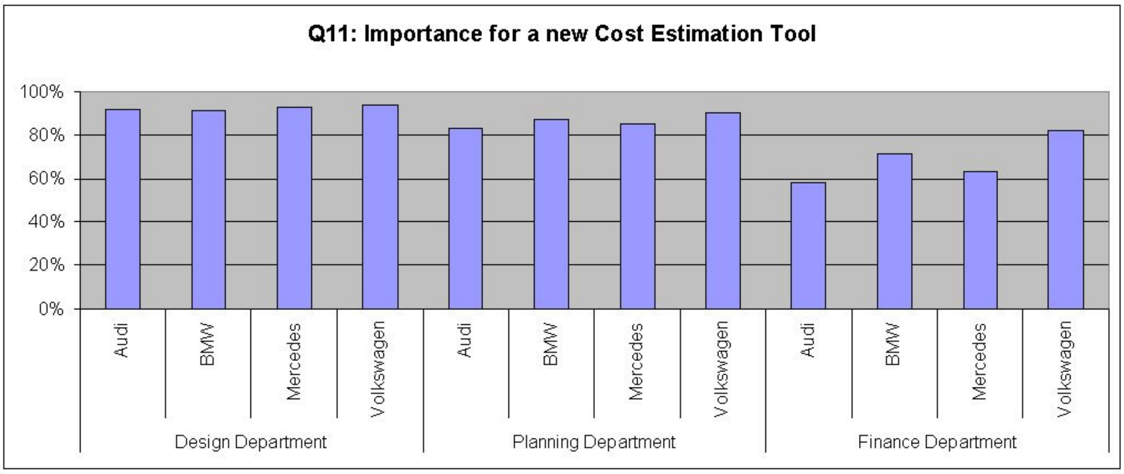


Table 2.2.10: Results of question 11.

Question 12: Do you expect that this new tool will have an impact on your decision making process?

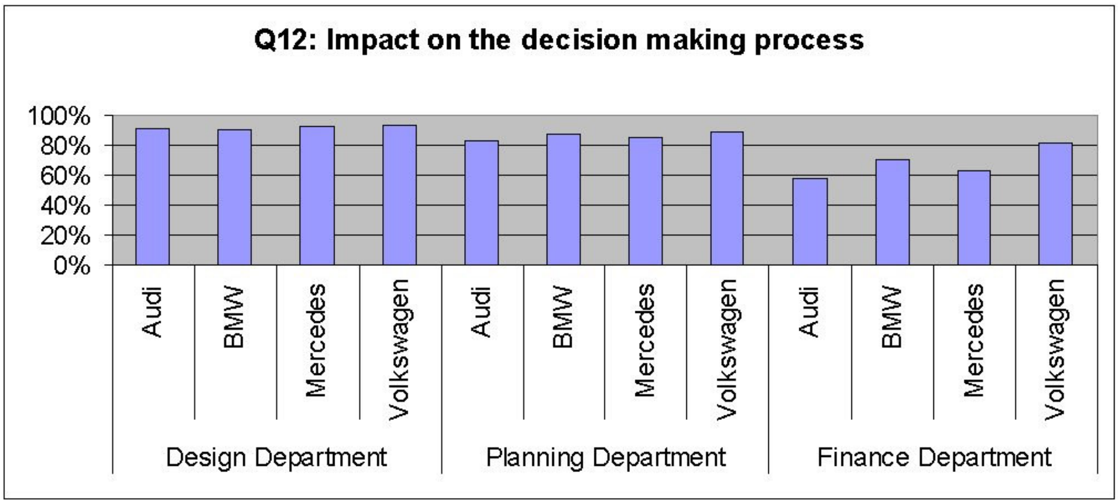


Table 2.2.11: Results of question 12.

3. Interview

3.1 Interview Outline

Interview Outline
1.General Topics (Design, Planning and Finance) 1a) The need of cost estimation methods. 1b) Unfamiliarity of Body-in-white designers with cost decision methodologies. 1c) Possibility of using Working Contents as a "common denominator" between Design, Planning and Finance. 1d) Possibility of transforming Working Contents into Joining Techniques. 1e) Joining Techniques as basis for a cost estimation methodology. 1f) Role of Joining Technique material in the manufacturing and cost estimation process. **2.Technical Topics (Design and Planning)** 2a) The research hypothesis: "It is possible to develop an estimating method on the basis of information contained in the specification data of BIW design concepts." 2b) Possibility of converting data content of the BIW specification into Working Contents. 2c) Ability of Body-in-white designer to apply Joining Techniques to design concepts in terms of technical aspects. 2d) Inability of Body-in-white designer to identify optimal combination of Joining Techniques of a design concept in terms of economic aspects. **3.Cost Topics (Planning and Finance)** 3a) Possibility of estimating manufacturing cost of new Body-in-white design concepts in the Early Phase of Product Development Process. 3b) Location of major portion of manufacturing cost of Body-in-white design concepts in Joining Technique process. 3c) Question of availability of relevant Joining Technique cost data. 3d) Reliability of available cost information.

Table 3.1.1: Interview Outline.

3.2 Results of Interviews

1. General Topics

1a) Is there a need for a cost estimation method in the Early Phase of the PDP?

	Design	Planning	Finance
Yes [%]	92	88	76
No [%]	8	12	24

1b) Are Body-in-white designers unfamiliar with cost decision methodologies?

	Design	Planning	Finance
Yes [%]	100	100	100
No [%]	0	0	0

1c) Can Working Contents be used as a "common denominator" between Design, Planning and Finance?

	Design	Planning	Finance
Yes [%]	94	97	93
No [%]	6	3	7

1d) Can Working Contents be transformed into Joining Techniques?

	Design	Planning	Finance
Yes [%]	87	92	89
No [%]	13	8	11

1e) Can Joining Techniques establish a basis for the cost estimation methodology?

	Design	Planning	Finance
Yes [%]	91	96	90
No [%]	9	4	10

1f) Does the material of the joining process play an important role in the manufacturing and cost estimating process?

	Design	Planning	Finance
Yes [%]	96	97	86
No [%]	4	3	14

Table 3.2.1: General Topics interview results.

2. Technical Topics

2a) Do you agree with the research hypothesis: “It is possible to develop an estimating method on the basis of information contained in the specification data of BIW design concepts."?

	Design	Planning
Yes [%]	96	89
No [%]	4	11

2b) Can the data content of the specifications be converted into Working Contents?

	Design	Planning
Yes [%]	87	92
No [%]	13	8

2c) Does the Body-in-white designer have the technical expertise to apply Joining Techniques to BIW design concepts?

	Design	Planning
Yes [%]	97	94
No [%]	3	6

2d) Is the Body-in-white designer able to identify the optimal combination of Joining Techniques of a design concept in terms of cost?

	Design	Planning
Yes [%]	5	8
No [%]	95	92

Table 3.2.2: Technical Topics interview results.

3. Cost Topics

3a) Can you estimate the manufacturing cost of new Body-in-white design concepts in the Early Phase of the Product Development Process?

	Planning	Finance
Yes [%]	14	19
No [%]	86	81

3b) Is the major portion of the manufacturing cost of a Body-in-white design concept located in the Joining Technique process?

	Planning	Finance
Yes [%]	92	87
No [%]	8	13

3c) Are relevant Joining Technique cost data available?

	Planning	Finance
Yes [%]	24	29
No [%]	76	71

3d) Are the available cost data reliable?

	Planning	Finance
Yes [%]	37	48
No [%]	63	52

Table 3.2.3: Cost Topics interview results.

4. Standardised Working Content Coefficient

Joining side Material:		Steel - Steel				Steel - High tensile Steel				Steel - Aluminium				Aluminium - Aluminium				Aluminium - High tensile steel			
No.	Joining Tech. / Costs	C_{st-st}	M_{st-st}	TC_{st-st}	$SWCC_{st-st}$	C_{st-hst}	M_{st-hst}	TC_{st-hst}	$SWCC_{st-hst}$	C_{st-alu}	M_{st-alu}	TC_{st-alu}	$SWCC_{st-alu}$	$C_{alu-alu}$	$M_{alu-alu}$	$TC_{alu-alu}$	$SWCC_{alu-alu}$	$C_{alu-hst}$	$M_{alu-hst}$	$TC_{alu-hst}$	$SWCC_{alu-hst}$
1.	Spot welding	0,00531	0,01137	0,01668	**1,00000**	0,006976	0,01613	0,02311	**1,38525**	--	--	--	--	0,005836	0,01642	0,02226	**1,33429**	--	--	--	--
2.	Spot weld-gluing	0,04587	0,09774	0,14361	**8,60971**	0,05829	0,12421	0,1825	**10,94125**	--	--	--	--	--	--	--	--	--	--	--	--
3.	MIG welding	0,006274	0,016476	0,02275	**1,36391**	0,006659	0,019712	0,026371	**1,58100**	--	--	--	--	0,00685	0,01856	0,02541	**1,52338**	--	--	--	--
4.	Tandem MIG welding	0,004502	0,0156	0,02010	**1,20516**	0,005516	0,018699	0,024215	**1,45174**	--	--	--	--	0,00484	0,016917	0,02176	**1,30438**	--	--	--	--
5.	MAG welding	0,007307	0,01965	0,02696	**1,61613**	0,00794	0,02083	0,02877	**1,72482**	--	--	--	--	0,006792	0,01737	0,02416	**1,44856**	--	--	--	--
6.	WIG welding	0,008218	0,03844	0,04666	**2,79724**	--	--	--	**--**	--	--	--	--	0,00866	0,04032	0,04898	**2,93645**	--	--	--	--
7.	Laser-welding (CO_2)	0,01459	0,02316	0,03775	**2,26319**	0,01488	0,02556	0,04044	**2,42446**	--	--	--	--	0,01519	0,02449	0,03968	**2,37890**	--	--	--	--
8.	Laser-welding (Diodes)	0,01523	0,03154	0,04677	**2,80396**	0,01594	0,033729	0,049669	**2,97776**	--	--	--	--	0,016882	0,03954	0,05642	**3,38261**	--	--	--	--
9.	Laser-welding (YAG)	0,008105	0,016757	0,02486	**1,49053**	0,01233	0,02837	0,0407	**2,44005**	--	--	--	--	0,010221	0,020616	0,03084	**1,84874**	--	--	--	--
10.	Projection welding	0,006545	0,01201	0,01856	**1,11241**	0,006782	0,01348	0,020262	**1,21475**	--	--	--	--	--	--	--	--	--	--	--	--
11.	Laser brazing	0,02047	0,02832	0,04879	**2,92506**	--	--	--	**--**	0,02075	0,029	0,04975	**2,98261**	--	--	--	--	0,02131	0,03001	0,05132	**3,07674**
12.	MAG brazing	0,00646	0,02318	0,02964	**1,77698**	--	--	--	**--**	--	--	--	--	--	--	--	--	--	--	--	--
13.	Punch riveting	0,007876	0,03111	0,03899	**2,33729**	--	--	--	**--**	0,007994	0,03404	0,042034	**2,52002**	0,008115	0,033119	0,04123	**2,47206**	0,008467	0,039309	0,04778	**2,86427**
14.	Blind riveting	0,011147	0,031415	0,04256	**2,55168**	0,012489	0,036898	0,049387	**2,96085**	0,012012	0,035149	0,047161	**2,82740**	0,011147	0,031757	0,04290	**2,57218**	0,011756	0,034933	0,04669	**2,79910**
15.	Clinching	0,006712	0,01786	0,02457	**1,47314**	--	--	--	**--**	0,007717	0,021122	0,028839	**1,72896**	0,006512	0,016561	0,02307	**1,38327**	0,008323	0,024659	0,03298	**1,97734**
16.	Flanging	0,018405	0,029021	0,04743	**2,84329**	0,020926	0,034294	0,05522	**3,31055**	0,019123	0,030913	0,050036	**2,99976**	0,018764	0,029638	0,04840	**2,90180**	0,020562	0,034204	0,05477	**3,28333**
17.	Cohesiveness gluing	0,011147	0,023593	0,03474	**2,08273**	0,011845	0,027348	0,039193	**2,34970**	0,0125411	0,02915	0,0416911	**2,49947**	0,012541	0,031107	0,04365	**2,61679**	0,011845	0,029164	0,04101	**2,45857**

Table 4.1: Calculation of the Standardised Working Content Coefficient.

Joining side Material:		Steel - Steel	Steel - High tensile Steel	Steel - Aluminium	Aluminium - Aluminium	Aluminium - High tensile steel
No.	Joining Tech. / SWCC	$SWCC_{st-st}$	$SWCC_{st-htst}$	$SWCC_{st-alu}$	$SWCC_{alu-alu}$	$SWCC_{alu-htst}$
1.	Spot welding	1,00000	1,38525	--	1,33429	--
2.	Spot weld-gluing	8,60971	10,94125	--	--	--
3.	MIG welding	1,36391	1,58100	--	1,52338	--
4.	Tandem MIG welding	1,20516	1,45174	--	1,30438	--
5.	MAG welding	1,61613	1,72482	--	1,44856	--
6.	WIG welding	2,79724	--	--	2,93645	--
7.	Laser-welding (CO_2)	2,26319	2,42446	--	2,37890	--
8.	Laser-welding (Diodes)	2,80396	2,97776	--	3,38261	--
9.	Laser-welding (YAG)	1,49053	2,44005	--	1,84874	--
10.	Projection welding	1,11241	1,21475	--	--	--
11.	Laser brazing	2,92506	--	2,98261	--	3,07674
12.	MAG brazing	1,77698	--	--	--	--
13.	Punch riveting	2,33729	--	2,52002	2,47206	2,86427
14.	Blind riveting	2,55168	2,96085	2,82740	2,57218	2,79910
15.	Clinching	1,47314	--	1,72896	1,38327	1,97734
16.	Flanging	2,84329	3,31055	2,99976	2,90180	3,28333
17.	Cohesiveness gluing	2,08273	2,34970	2,49947	2,61679	2,45857

Table 4.2: Standardised Working Content Coefficient table.

5. Joining Techniques and Material Combinations

Matrix of approved Joining Techniques and material combinations

	Joining Techn. / Material	Steel/Steel	Steel/ High tensile steel	Steel/ Aluminium	Aluminium/ Aluminium	High tensile steel/ Aluminium	High tensile Steel/ High tensile steel	Aluminium/ Steel-Sandwich	Steel/ Composites	Aluminium/ Composites	Steel/CFK	CFK/CFK
Warm Joining Techniques	1. Spot welding	in serial production	in serial production		in serial production		in serial production	in development	in development			
	2. Spot weld-gluing	in serial production	in serial production		in development		in serial production	in development	in development			
	3. MIG welding	in serial production	in serial production		in serial production		in serial production					
	4. Tandem MIG welding	in serial production	in serial production		in serial production		in serial production					
	5. MAG welding	in serial production	in serial production		in serial production		in serial production					
	6. WIG welding	in serial production	technical bases are developed		in serial production		in serial production					
	7. Laser welding (CO_2)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	8. Laser welding (Diodes)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	9. Laser welding (YAG)	in serial production	in serial production	in development	in serial production	in development	in serial production					
	10. Projection welding	in serial production	in serial production		in development		in serial production					
	11. Laser brazing	in serial production	technical bases are developed	in serial production	in development	in serial production	technical bases are developed					
	12. MAG brazing	in serial production	in development	in development		in development	in development					
Cold Joining Techniques	13. Punch-riveting	in serial production	in development	in serial production	in serial production	in serial production	in development	technical bases are developed	technical bases are developed	technical bases are developed	in development	in development
	14. Blind-riveting	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
	15. Clinching	in serial production	in development	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development	in development
	16. Flanging	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development
Gluing	17. Cohesiveness-gluing	in serial production	in serial production	in serial production	in serial production	in serial production	in serial production	in development	in development	in development	in development	in development

Legend: in serial production; technical bases are developed; in development; not possible

Table 5.1: Matrix of approved Joining Techniques and material combinations.

6. Complexity Sheets

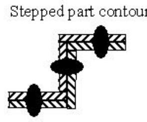
Spot welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Variation of blank sheet thickness 0%, two-blank sheet-welding of equal blank sheet thickness, blank sheet thickness > 1,5mm. Effective joining width according to DIN: 20mm < effective width of the joining blank sheet. Blank sheet surface without discoloration, free of oil, free of grease,without coating, not galvanised. Great degree of freedom for the welding gun, little steel in "secondary welding gun window", easily positioning of the welding gun because of an appropriate blank sheet contour ⇒ plane part contour.	Plane part contour  100% cycle time
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Two-blank sheet-welding of different blank sheet thickness 0,7mm < blank sheet thickness < 1,5mm, variation of blank sheet thickness < 20%. Effective joining width outside of DIN reference, effective joining width narrow, 20mm > effective width of the joining blank sheet. Blank sheet surface without discoloration, without coating. Average volume of steel in the "secondary welding gun window", normal size of the welding gun (length of piole X < 800m), normal positioning of welding gun because of an appropriate blank sheet contour ⇒ curved part contour.	Curved part contour  125% cycle time
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Two or three-blank sheet-welding of equal blank sheet thickness 0,7mm < blank sheet thickness < 1,5mm, variation of blank sheet thickness > 20%. Joining width under limit, 15mm > effective width of the joining blank sheet. Blank sheet surface with discoloration, heavily oiled, greased, galvanised. Shortage of space , great amount of steel in "secondary welding gun window", big welding gun (length of piole X > 800mm), difficult positioning of welding gun because of a complicate blank sheet contour ⇒ stepped part contour.	Stepped part contour  150% cycle time

Table 6.1: JS Coefficient for JT spot welding.

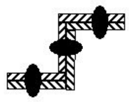
Spot weld-gluing			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Variation of blank sheet thickness 0%, two-blank sheet-weld-gluing of equal blank sheet thickness, 0,7mm < blank sheet thickness < 1,5mm, Effective joining width according DIN, 25 mm < effective width of the joining blank sheet. Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised, no dry-film lubricant, temperature of the weldment: temperature of joining part is equal to temperature of glue (ΔT = 0°C). Great degree of freedom for the welding and gluing gun, little steel in "secondary welding gun window", easily positioning of the guns because of an appropriate blank sheet contour ⇒ plane part contour.	Plane part contour  100% cycle time
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Variation of blank sheet thickness < 20%. Two-blank sheet-weld-gluing of different blank sheet thickness, 0,7mm < blank sheet thickness < 1,5mm. Effective joining width outside of DIN reference, effective joining width narrow, 25mm > effective width of the joining blank sheet. Blank sheet surface covert with oil: < 3g/m² steel, < 0,8g/m² aluminium,dry-film lubricant < 1,5g/m² for steel and aluminium, temperature of the weldment: temperature of joining part is lower as temperature of glue (ΔT = 10°C). Average volume of steel in the "secondary welding gun window", normal welding gun size (length of piole < 800mm), normal positioning of welding and gluing gun because of an appropriate blank sheet contour ⇒curved part contour.	Curved part contour  125% cycle time
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Variation of blank sheet thickness > 20%, two or three-blank sheet-weld-gluing of equal blank sheet thickness, blank sheet thickness < 0,7 mm. Joining width under limit, 20mm > effective width of the joining blank sheet. Blank sheet surface with discoloration, greased, galvanised, blank sheet surface covert with oil: > 3g/m² steel, > 0,8g/m² aluminium,dry-film lubricant >1,5g/m² for steel and aluminium, temperature of the weldment: temperature of joining part is lower as temperature of glue (ΔT = 15°C). Great amount of steel in the "secondary welding gun window", big welding gun (length of piole > 800mm), difficult positioning of welding and gluing gun because of a complicate blank sheet contour ⇒ stepped part contour.	Stepped part contour  150% cycle time

Table 6.2: JS Coefficient for JT spot weld-gluing.

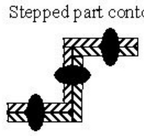
MIG welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Welding of two blank sheets, blank sheet thickness > 1,0mm, variation of blank sheet thickness 0%, no problem with feed rate after DIN.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 20mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 15%, two-blank sheet-welding of different blank sheet thickness 0,8mm < blank sheet thickness < 1,0mm, normal feed rate according to DIN.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 20mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Blank sheet thickness thin: blank sheet thickness < 0,8mm, variation of blank sheet thickness > 20%, problems with feed rate (burn out).	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 15mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised, difficult part contour.	
	4. Accessibility:	Welding position: fall and rise weld, complicate blank sheet contour ⇒ stepped part contour.	

Table 6.3: JS Coefficient for JT MIG welding.

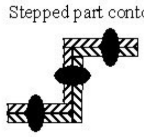
Tandem MIG welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Welding of two blank sheets, blank sheet thickness > 1,0mm, variation of blank sheet thickness 0%, no problem with feed rate after DIN.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 25mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), normal blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 15%, two-blank sheet-welding of different blank sheet thickness 0,8mm < blank sheet thickness < 1,0mm, normal feed rate after DIN.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 25mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Blank sheet thickness thin: blank sheet thickness < 0,8 mm, variation of blank sheet thickness > 15%, problems with feed rate (burn out).	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 20mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised, difficult part contour.	
	4. Accessibility:	Welding position: fall and rise weld ,complicate blank sheet contour ⇒ stepped part contour.	

Table 6.4: JS Coefficient for JT tandem MIG welding.

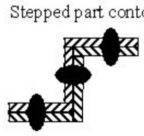
MAG welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Welding of two blank sheets, blank sheet thickness > 1,0mm, variation of blank sheet thickness 0%, no problem with feed rate after DIN.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 20mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), simple blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 15%, two-blank sheet-welding of different blank sheet thickness 0,8mm < blank sheet thickness < 1,0mm, normal feed rate according to DIN.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 20mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), normal blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Blank sheet thickness thin: blank sheet thickness < 0,8mm, variation of blank sheet thickness > 20%, problems with feed rate (burn out).	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 15mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised, difficult part contour.	
	4. Accessibility:	Welding position: fall and rise weld ,complicate blank sheet contour ⇒ stepped part contour.	

Table 6.5: JS Coefficient for JT MAG welding.

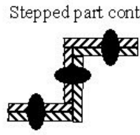
WIG welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Welding of two blank sheets, blank sheet thickness > 1,1mm, variation of blank sheet thickness < 5 %, no problem with feed rate after DIN.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 20mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 20%, two-blank sheet-welding of different blank sheet thickness 0,8mm < blank sheet thickness < 1,1mm, normal feed rate according to DIN.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 20mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Welding position of the blank sheets: horizontal position (tray position), blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Blank sheet thickness thin: blank sheet thickness < 0,8mm, variation of blank sheet thickness > 20%.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 15mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised, difficult part contour.	
	4. Accessibility:	Welding position: fall and rise weld, complicate blank sheet contour ⇒ stepped part contour.	

Table 6.6: JS Coefficient for JT WIG welding.

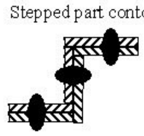
Laser welding (CO_2, Diodes or YAG)			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	No variation of blank sheet thickness, two-blank sheet-welding of equal blank sheet thickness, blank sheet thickness > 1,3mm.	Plane part contour  100% cycle time
	2. Effective width:	Large contact surface > 20mm according to DIN reference.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Plane surface, great degree of freedom for the press-on-roll, possibility for degasification, no extra plate necessary if part has a high stiffness, blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 10%, two-blank sheet-welding of different blank sheet thickness, 0,9mm < blank sheet thickness < 1,3mm.	Curved part contour  125% cycle time
	2. Effective width:	Normal contact surface < 20mm according to DIN reference.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Normal degree of freedom for the press-on-roll, critical radius of weldment is bigger than press-on-roll radius radius, linear force transmission of the press-on-roll, blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Great variation of blank sheet thickness > 10%, two or three-blank sheet-welding of equal blank sheet thickness 0,7mm < blank sheet thickness > 0,9mm.	Stepped part contour  150% cycle time
	2. Effective width:	Small contact surface < 16mm according to DIN reference.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, galvanised.	
	4. Accessibility:	Shortage of space , small degree of freedom for the press-on-roll, critical radius of weldment is equal to press-on-roll radius, vertical force transmission of the press-on-roll , blank sheet contour ⇒ stepped part contour.	

Table 6.7: JS Coefficient for JT laser (CO_2, Diodes and YAG) welding.

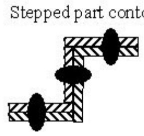
Projection welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, welding of equal blank sheet thickness, blank sheet thickness > 1,4mm.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width: nut diameter < 4mm.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised.	
	4. Accessibility:	Great degree of freedom, single or series welding: weldment structure in plane (maximum 4 nuts), simple blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 10%, welding of equal blank sheet thickness, 0,8mm < blank sheet thickness < 1,4mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width: nut diameter = 4mm.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating.	
	4. Accessibility:	Normal degree of freedom, single or series welding: single welding in one plane (1 nut), proportion thread diameter to whole diameter : M6→ 8mm, M8 → 10mm, M10 →12mm, blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 15%, welding of equal blank sheet thickness, blank sheet thickness < 0,8mm.	Stepped part contour  150% cycle time
	2. Effective width:	Effective joining width: nut diameter > 4mm	
	3. Surface condition:	Different metal surface, blank sheet surface with discoloration, heavily oiled, greased, galvanised.	
	4. Accessibility:	Shortage of space, difficult weldment structure, proportion thread diameter to whole diameter : M6→ 9mm, M8 → 11mm, M10 →13mm, complicate blank sheet contour ⇒ stepped part contour.	

Table 6.8: JS Coefficient for JT projection welding.

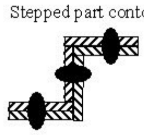
Laser brazing			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, two-blank sheet-brazing of equal blank sheet thickness, blank sheet thickness > 1,1mm.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 15mm < effective width of the joining blank sheet, fitting accuracy: horizontal seam < 0,3mm seam length.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised, because of the generated heat short soldering seams length: 10mm < X < 30mm .	
	4. Accessibility:	Great degree of freedom for the laser brazing gun, easily positioning of the welding gun because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 15%, two-blank sheet-brazing of different blank sheet thickness 0,8mm < blank sheet thickness < 1,1mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 15 mm > effective width of the joining blank sheet, fitting accuracy: vertical or horizontal seam < 0,6mm seam length.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating, because of the generated heat normal soldering seams length: 30mm < X < 50mm .	
	4. Accessibility:	Normal positioning of laser brazing gun because of an appropriate blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness > 15%, two-blank sheet-brazing of different blank sheet thickness, blank sheet thickness < 0,8mm.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 10mm < effective width of the joining blank sheet, fitting accuracy: vertical seam < 0,6mm seam length..	
	3. Surface condition:	Blank sheet surface with discoloration, oiled, greased, galvanised, because of the generated heat long soldering seams length > 50mm.	
	4. Accessibility:	Shortage of space, difficult positioning of laser brazing gun because of a complicate blank sheet contour ⇒ stepped part contour.	

Table 6.9: JS Coefficient for JT laser brazing.

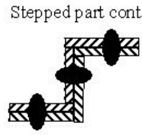
MIG brazing			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, two-blank sheet-brazing of equal blank sheet thickness, blank sheet thickness > 1,0mm.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 12mm < effective width of the joining blank sheet, fitting accuracy: horizontal seam < 0,5mm seam length.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised, because of the generated heat short soldering seams length: 8mm < X < 25mm .	
	4. Accessibility:	Great degree of freedom for the MIG brazing gun, easily positioning of the welding gun because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 20%, two-blank sheet-brazing of different blank sheet thickness 0,8mm < blank sheet thickness < 1,0mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 12 mm > effective width of the joining blank sheet, fitting accuracy: vertical or horizontal seam < 0,7mm seam length.	
	3. Surface condition:	Blank sheet surface without discoloration, without coating, because of the generated heat normal soldering seams length: 25mm < X < 40mm .	
	4. Accessibility:	Normal positioning of MIG brazing gun because of an appropriate blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness > 20%, two-blank sheet-brazing of different blank sheet thickness, blank sheet thickness < 0,8mm.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 10mm > effective width of the joining blank sheet, fitting accuracy: vertical seam < 0,8mm seam length..	
	3. Surface condition:	Blank sheet surface with discoloration, oiled, greased, galvanised, because of the generated heat long soldering seams length > 40mm.	
	4. Accessibility:	Shortage of space, difficult positioning of MIG brazing gun because of a complicate blank sheet contour ⇒ stepped part contour.	

Table 6.10: JS Coefficient for JT MIG brazing.

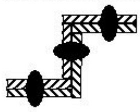
Punch and blind riveting			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, two-blank sheets of equal blank sheet thickness, blank sheet thickness > 1,5mm,	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 22mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, material quality: steel.	
	4. Accessibility:	Great degree of freedom for the riveting gun, size of riveting gun < 200mm, easily positioning of the riveting gun because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 20%, two-blank sheet of different blank sheet thickness, 1,5mm > blank sheet thickness > 1,0mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width according to DIN reference, effective width of the joining blank sheet = 22mm .	
	3. Surface condition:	Blank sheet surface without discoloration, material quality: 5000 alloy, aluminium.	
	4. Accessibility:	Normal size of the riveting gun between 200-400mm, normal positioning of riveting gun because of an appropriate blank sheet contour ⇒curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness > 20%, two blank sheets of equal blank sheet thickness, blank sheet thickness < 1,0mm risk of punching wholes possible because of the lack of forming material.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, effective width of the joining blank sheet < 22mm.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, material quality: cast iron, 6000 alloy, brittle material, aluminium-steel compounds.	
	4. Accessibility:	Shortage of space, big riveting gun > 400mm, difficult positioning of riveting gun because of a complicate blank sheet contour ⇒ stepped part contour.	

Table 6.11: JS Coefficient for JT punch and blind brazing.

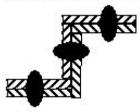
Clinching			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, two-blank sheets of equal blank sheet thickness, blank sheet thickness > 1,4mm,	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according DIN reference, 22mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, material quality: steel.	
	4. Accessibility:	Great degree of freedom for the riveting gun, size of riveting gun < 200mm, easily positioning of the clinching gun because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 20%, two-blank sheet of different blank sheet thickness, 1,4mm > blank sheet thickness > 1,0mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width according to DIN reference, effective width of the joining blank sheet = 22mm .	
	3. Surface condition:	Blank sheet surface without discoloration, material quality: 5000 alloy, aluminium.	
	4. Accessibility:	Normal size of the clinching gun between 200-400mm, normal positioning of riveting gun because of an appropriate blank sheet contour ⇒curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness > 20%, two blank sheets of equal blank sheet thickness, blank sheet thickness < 1,0mm risk of punching wholes possible because of the lack of forming material.	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, effective width of the joining blank sheet < 22mm.	
	3. Surface condition:	Blank sheet surface with discoloration, heavily oiled, greased, material quality: cast iron, 6000 alloy, brittle material, aluminium-steel compounds.	
	4. Accessibility:	Shortage of space, big clinching gun > 400mm, difficult positioning of clinching gun because of complicate blank sheet contour ⇒ stepped part contour.	

Table 6.12: JS Coefficient for JT punch and blind brazing.

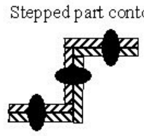
Flanging			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness 0%, two-blank sheet-flanging of equal blank sheet thickness, 0,7mm < blank sheet thickness < 1,0mm.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 25mm < effective width of the joining blank sheets.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating.	
	4. Accessibility:	Great degree of freedom for the flanging rolls, easily positioning of the flanging rolls because of an appropriate blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 7%, two-blank sheet-flanging of different blank sheet thickness, 1,0mm < blank sheet thickness < 1,4mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 20mm < effective width of the joining blank sheets.	
	3. Surface condition:	Blank sheet surface without discoloration, free of grease, without coating.	
	4. Accessibility:	Normal degree of freedom for the flanging rolls, normal positioning of the flanging rolls because of an appropriate blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Variation of blank sheet thickness < 11%, two-blank sheet-flanging of different blank sheet thickness, blank sheet thickness > 1,4mm.	Stepped part contour  150% cycle time
	2. Effective width:	Effective joining width according to DIN reference, 15mm < effective width of the joining blank sheets.	
	3. Surface condition:	Blank sheet surface with discoloration, covert with oil and grease.	
	4. Accessibility:	Small degree of freedom for the flanging rolls, difficult positioning of the flanging rolls because of a complicate blank sheet contour ⇒ stepped part contour.	

Table 6.13: JS Coefficient for JT flanging.

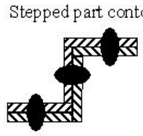
Cohesiveness gluing			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:**	Two-blank sheet-gluing of equal blank sheet thickness, 1,5mm < blank sheet thickness < 2,5mm.	Plane part contour  100% cycle time
	2. Effective width:	Effective joining width according to DIN, 25mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised, no dry-film lubricant, temperature of the blank sheets: temperature of blank sheet is equal to temperature of glue ($\Delta T = 0°C$).	
	4. Accessibility:	Great degree of freedom for the gluing gun, easily positioning of the gun because of an appropriate contact surface and blank sheet contour ⇒ plane part contour.	
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:**	Two-blank sheet-gluing of different blank sheet thickness, 1,0mm < blank sheet thickness < 1,5mm.	Curved part contour  125% cycle time
	2. Effective width:	Effective joining width outside of DIN reference, effective joining width narrow, 25mm > effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface covert with oil: < 3g/m² steel, < 0,8g/m² aluminium, dry-film lubricant < 1,5g/m² for steel and aluminium, temperature of the blank sheet: temperature of blank sheet is lower as temperature of glue ($\Delta T = 10°C$).	
	4. Accessibility:	Normal gluing gun size, normal positioning of gluing gun because of an appropriate contact surface and blank sheet contour ⇒ curved part contour.	
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:**	Two or three-blank sheet-gluing of equal blank sheet thickness, blank sheet thickness < 1,0mm,	Stepped part contour  150% cycle time
	2. Effective width:	Joining width under limit, 15mm < effective width of the joining blank sheet.	
	3. Surface condition:	Blank sheet surface with discoloration, greased, galvanised, blank sheet surface covert with oil: > 3g/m² steel, > 0,8g/m² aluminium, dry-film lubricant > 1,5g/m² for steel and aluminium, temperature of the blank sheet: temperature of blank sheet is lower as temperature of glue ($\Delta T = 15°C$).	
	4. Accessibility:	Big gluing gun size, difficult positioning of gluing gun because of a complicate contact surface and blank sheet contour ⇒ stepped part contour.	

Table 6.14: JS Coefficient for JT gluing.

7. Joining Technique Cost Templates

7.1 Spot welding

Joining Technique:	**Resistance spot welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of spot welding.			
Investment cost:	198.744 EURO		per spot:	0,00531 €/spot
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1412 spots/hour.			
Manufacturing costs:				
	Type/Unit	Consumption (units/hour)	Costs (EURO/unit)	Costs (EURO/hour)
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,20 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,0016	2.556,46 €	4,09 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**8,58 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**16,06 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	44 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	51 sec	(1412 spots/hour)	per spot:	0,01137 €/spot

Table 7.1.1: JT cost template for JT spot welding, steel-steel.

Joining Technique:	**Resistance spot welding**		**Steel - High tensile Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of spot welding.			
Investment cost:	198.744 EURO		per spot:	0,006976 €/spot
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1075 spots/hour.			
Manufacturing costs:				
	Type/Unit	Consumption (units/hour)	Costs (EURO/unit)	Costs (EURO/hour)
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,002109	2.556,46 €	5,39 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**9,86 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**17,34 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	60 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	67 sec	(1075 spots/hour)	per spot:	0,01613 €/spot

Table 7.1.2: JT cost template for JT spot welding, steel-high tensile steel.

Joining Technique:	**Resistance spot welding**		**H.tensileSteel - H.tensile. Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **high tensile steel** sheet components by utilisation of a spot welding.			
Investment cost:	**198.744 EURO**		**per spot:**	**0,006666 €/spot**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1125 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,002391	2.556,46 €	6,11 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**10,58 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**18,06 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	57 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	64 sec	(1125 spots/hour)	**per spot:**	**0,016053 €/spot**

Table 7.1.3: JT cost template for JT spot welding, high tensile steel-high tensile steel.

Joining Technique:	**Resistance spot welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of spot welding.			
Investment cost:	**198.744 EURO**		**per spot:**	**0,005836 €/spot**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1285 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Two records winding mechanism	devices/h	0,0012101	7.209,22 €	8,72 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**13,62 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**21,10 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	49 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	56 sec	(1285 spots/hour)	**per spot:**	**0,01642 €/spot**

Table 7.1.4: JT cost template for JT spot welding, aluminium-aluminium.

7.2 Spot weld-gluing

Joining Technique:	**Spot weld-gluing**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of spot weld-gluing.			
Investment cost:	**1.483.044 EURO**		**per spot:**	**0,04587 €/spot**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1220 glue-spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	Betamate 1480	2,25	17,90 €	40,26 €
- consumption	(10 g/m)	10x225 = 2250g		
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	8,6 KVA/51%	8	0,047 €	0,38 €
- Glue heating	6,0KW/95%			
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,20 €
- Electricity for turntable	4 KWh/6,4%	2,8	0,047 €	0,13 €
- Electricity for heater	150KW/92%	150	0,047 €	7,05 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	6 bar/ 2ltr. Per spot	5000	0,00005 €	0,25 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	3,6091	2.556,46 €	3,61 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,03 €
- 5 Clinch points per part		225	0,03 €	7,31 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**63,29 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.483.044 €**	55,96 €
Sum manufacturing cost per hour with depreciation:				**119,25 €**
Example: **1000mm joining length (20 welding spots/ Spot distance 50mm/ 10 g/m / width 50 mm)**				
- Gluing time	8 sec			
- Joining time:	44 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	59 sec	(1220 glue-spots/hour)	**per spot:**	**0,09774 €/spot**

Table 7.2.1: JT cost template for JT spot weld-gluing, steel-steel.

Joining Technique:	**Spot weld-gluing**		**Steel - High tensile Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of spot weld-gluing.			
Investment cost:	**1.483.044 EURO**		**per spot:**	**0,05829 €/spot**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 960 glue-spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	Betamate 1480	2,25	17,90 €	40,26 €
- consumption	(10 g/m)	10x225 = 2250g		
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	8,6 KVA/51%	8	0,047 €	0,38 €
- Glue heating	6,0KW/95%			
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,20 €
- Electricity for turntable	4 KWh/6,4%	2,8	0,047 €	0,13 €
- Electricity for heater	150KW/92%	150	0,047 €	7,05 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	6 bar/ 2ltr. Per spot	5000	0,00005 €	0,25 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	3,6091	2.556,46 €	3,61 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,03 €
- 5 Clinch points per part		225	0,03 €	7,31 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**63,29 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.483.044 €**	55,96 €
Sum manufacturing cost per hour with depreciation:				**119,25 €**
Example: **1000mm joining length (20 welding spots/ Spot distance 50mm/ 10 g/m / width 50 mm)**				
- Gluing time	8 sec			
- Joining time:	60 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	75 sec	(960 glue-spots/hour)	**per spot:**	**0,12421 €/spot**

Table 7.2.2: JT cost template for JT spot weld-gluing, steel-high tensile steel.

7.3 MIG welding

Joining Technique:	**MIG welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of MIG welding.			
Investment cost:	**184.069 EURO**		**per seam:**	**0,006274 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1107 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	AlSi5/ 1,2mm	0,5406	4,00 €	2,16 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	3,6	0,047 €	0,17 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	350	0,00005 €	0,02 €
- Inert gas	Argon/ 21l/min	954	0,001 €	0,954 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 600 seams	1,6615	2,25 €	3,74 €
- Gas nozzle	2 per 5000 seams	0,04989	5,63 €	0,28 €
- Brass core	1 per 15000 seams	0,06817	23,08 €	1,57 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**11,32 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**184.069 €**	6,92 €
Sum manufacturing cost per hour with depreciation:				**18,24 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	48 sec			
- Robot time:	12 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	65 sec	(1107 seams/hour)	**per seam:**	**0,016476 €/seam**

Table 7.3.1: JT cost template for JT MIG welding, steel-steel.

Joining Technique:	**MIG welding**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheets, one of **steel** and one of **high tensile steel**, by utilisation of MIG welding.			
Investment cost:	**184.069 EURO**		**per seam:**	**0,006659 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1043 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	AlSi5/ 1,2mm	0,5406	4,00 €	2,16 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	3,6	0,047 €	0,17 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	350	0,00005 €	0,02 €
- Inert gas	Argon/ 21l/min	954	0,001 €	0,954 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 500 seams	2,1615	2,25 €	4,86 €
- Gas nozzle	2 per 5000 seams	0,08189	5,63 €	0,46 €
- Brass core	1 per 15000 seams	0,06817	23,08 €	1,57 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**13,64 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**184.069 €**	6,92 €
Sum manufacturing cost per hour with depreciation:				**20,56 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	52 sec			
- Robot time:	12 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	69 sec	(1043 seams/hour)	**per seam:**	**0,019712 €/seam**

Table 7.3.2: JT cost template for JT MIG welding, steel-high tensile steel.

Joining Technique:	**MIG welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of MIG welding.			
Investment cost:	**184.069 EURO**		**per seam:**	**0,006850 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1014 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	AlSi5/ 1,2mm	0,5406	4,00 €	2,16 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	5,4	0,047 €	0,25 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas	Argon/ 18l/min	854	0,001 €	0,854 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 500 seams	1,8615	2,25 €	4,19 €
- Gas nozzle	2 per 3500 seams	0,07789	5,63 €	0,44 €
- Brass core	1 per 15000 seams	0,06817	23,08 €	1,57 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**11,90 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**184.069 €**	6,92 €
Sum manufacturing cost per hour with depreciation:				**18,82 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	54 sec			
- Robot time:	12 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	71 sec	(1014 seams/hour)	**per seam:**	**0,018560€/seam**

Table 7.3.3: JT cost template for JT MIG welding, aluminium-aluminium.

7.4 Tandem MIG welding

Joining Technique:	**Tandem MIG welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Tandem MIG welding.			
Investment cost:	**214.747 EURO**		**per seam:**	**0,004502 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1800 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	CuSi3/ 1,0mm	2,475	4,00 €	9,90 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	3,6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	7,2	0,047 €	0,34 €
- Electricity for turntable	4 KWh/%	3	0,047 €	0,14 €
- Inert gas	Argon/ 25l/min	2247	0,001 €	2,247 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 300 seams	0,675	2,25 €	1,52 €
- Gas nozzle	1 per 10000 seams	0,027	30,00 €	0,81 €
- Brass core	1 per 7000 seams	0,05935	46,16 €	2,74 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**20,01 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**214.747 €**	8,08 €
Sum manufacturing cost per hour with depreciation:				**28,09 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	32 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	40 sec	(1800 seams/hour)	**per seam:**	**0,01560 €/seam**

Table 7.4.1: JT cost template for JT Tandem MIG welding, steel-steel.

Joining Technique:	Tandem MIG welding		Steel - High tensile steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheets, one of **steel** and one of **high tensile steel**, by utilisation of Tandem MIG welding.			
Investment cost:	214.747 EURO		per seam:	0,005516 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1469 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	CuSi3/ 1,0mm	2,475	4,00 €	9,90 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	3,6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	7,2	0,047 €	0,34 €
- Electricity for turntable	4 KWh/%	3	0,047 €	0,14 €
- Inert gas	Argon/ 25l/min	2947	0,001 €	2,947 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 300 seams	0,375	2,25 €	0,84 €
- Gas nozzle	1 per 10000 seams	0,067	30,00 €	2,01 €
- Brass core	1 per 7000 seams	0,01935	46,16 €	0,89 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**19,39 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**214.747 €**	8,08 €
Sum manufacturing cost per hour with depreciation:				**27,47 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	41 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	49 sec	(1469 seams/hour)	per seam:	0,018699 €/seam

Table 7.4.2: JT cost template for JT Tandem MIG welding, steel-high tensile steel.

Joining Technique:	Tandem MIG welding		Aluminium - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Tandem MIG welding.			
Investment cost:	214.747 EURO		per seam:	0,004840 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1674 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	S-AlSi5/ 1,2mm	2,175	4,00 €	8,70 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	4,3	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	7,2	0,047 €	0,34 €
- Electricity for turntable	4 KWh/%	3	0,047 €	0,14 €
- Inert gas	Argon/ 27l/min	2747	0,001 €	2,747 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 800 seams	0,675	2,25 €	1,52 €
- Gas nozzle	1 per 15000 seams	0,027	30,00 €	0,81 €
- Brass core	1 per 700 seams	0,07945	46,16 €	3,67 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**20,24 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**214.747 €**	8,08 €
Sum manufacturing cost per hour with depreciation:				**28,32 €**
Example: 1000mm joining length (20 seams à 10mm/ seams distance 40mm)				
- Joining time:	35 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	43 sec	(1674 seams/hour)	per seam:	0,016917 €/seam

Table 7.4.3: JT cost template for JT Tandem MIG welding, aluminium-aluminium.

7.5 MAG welding

Joining Technique:	MAG welding		Steel - Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of MAG welding.			
Investment cost:	**199.069 EURO**		**per seam:**	**0,007307 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1028 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	G3Si1/ 0,9mm	0,8907	1,10 €	0,98 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	10	0,047 €	0,47 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas	Argon/ 20l/min	854	0,001 €	0,854 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 1200 seams	0,252	0,59 €	0,15 €
- Gas nozzle	2 per 10000 seams	0,3155	6,14 €	1,94 €
- Brass core	1 per 50000 seams	0,0668	6,49 €	0,43 €
- Splash guard	1 per 10000 seams	0,1315	2,56 €	0,34 €
- Wire core	1 per 25000 seams	0,2745	13,34 €	3,66 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**13,29 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**199.069 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**20,77 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	50 sec			
- Robot time:	15 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	70 sec	(1028 seams/hour)	**per seam:**	**0,01965 €/seam**

Table 7.5.1: JT cost template for JT MAG welding, steel-steel.

Joining Technique:	MAG welding		Steel - High tensile Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of MAG welding.			
Investment cost:	**199.069 EURO**		**per seam:**	**0,007940 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 946 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	G3Si1/ 0,9mm	0,8907	1,10 €	0,98 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	10	0,047 €	0,47 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas	Argon/ 20l/min	854	0,001 €	0,854 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 1200 seams	0,272	0,59 €	0,16 €
- Gas nozzle	2 per 10000 seams	0,3455	6,14 €	2,12 €
- Brass core	1 per 50000 seams	0,0768	6,49 €	0,50 €
- Splash guard	1 per 10000 seams	0,2315	2,56 €	0,59 €
- Wire core	1 per 25000 seams	0,2745	13,34 €	3,66 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**12,79 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**199.069 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**20,27 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	56 sec			
- Robot time:	15 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	76 sec	(946 seams/hour)	**per seam:**	**0,02083 €/seam**

Table 7.5.2: JT cost template for JT MAG welding, steel-high tensile steel.

Joining Technique:	**MAG welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of MAG welding.			
Investment cost:	**199.069 EURO**		**per seam:**	**0,006792 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1106 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	G3Si1/ 0,9mm	0,5406	4,00 €	2,16 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/51%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/52%	3,6	0,047 €	0,17 €
- Electricity for turntable	4 KWh/23%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas	Argon/ 18l/min	798	0,001 €	0,798 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 1200 seams	0,252	0,59 €	0,15 €
- Gas nozzle	2 per 10000 seams	0,3155	6,14 €	1,94 €
- Brass core	1 per 50000 seams	0,0668	6,49 €	0,43 €
- Splash guard	1 per 10000 seams	0,1315	2,56 €	0,34 €
- Wire core	1 per 25000 seams	0,2145	13,34 €	2,86 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**12,30 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**199.069 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**19,78 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	48 sec			
- Robot time:	12 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	65 sec	(1106 seams/hour)	**per seam:**	**0,01737 €/seam**

Table 7.5.3: JT cost template for JT MAG welding, aluminium-aluminium.

7.6 WIG welding

Joining Technique:	**WIG welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of WIG welding.			
Investment cost:	**214.747 EURO**		**per seam:**	**0,008218 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 986 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	W3Si1/ 7mm	2,475	4,10 €	10,15 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	10	0,047 €	0,47 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water				
- Inert gas	15l/min	1154	0,011 €	12,694 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 300 seams	0,6752	2,26 €	1,53 €
- Gas nozzle	1 per 10000 seams	0,02755	30,14 €	0,83 €
- Teflon core	1 per 7000 seams	0,05935	46,49 €	2,76 €
b) Labour	Minutes	1	1,02 €	1,02 €
Sum manufacturing cost per hour without depreciation:				**29,83 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**214.747 €**	8,08 €
Sum manufacturing cost per hour with depreciation:				**37,91 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	53 sec			
- Robot time:	15 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	73 sec	(986 seams/hour)	**per seam:**	**0,03844 €/seam**

Table 7.6.1: JT cost template for JT WIG welding, steel-steel.

Joining Technique:	**WIG welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of WIG welding.			
Investment cost:	**214.747 EURO**		**per seam:**	**0,00866 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 935 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	W3Si1/ 7mm	2,475	4,10 €	10,15 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	10	0,047 €	0,47 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water				
- Inert gas	15l/min	1134	0,011 €	12,474 €
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 300 seams	0,682	2,26 €	1,54 €
- Gas nozzle	1 per 10000 seams	0,02755	30,14 €	0,83 €
- Teflon core	1 per 7000 seams	0,05935	46,49 €	2,76 €
b) Labour	Minutes	1	1,02 €	1,02 €
Sum manufacturing cost per hour without depreciation:				**29,62 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**214.747 €**	8,08 €
Sum manufacturing cost per hour with depreciation:				**37,70 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	57 sec			
- Robot time:	15 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	77 sec	(935 seams/hour)	**per seam:**	**0,04032 €/seam**

Table 7.6.2: JT cost template for JT WIG welding, steel-steel.

7.7 Laser CO_2 welding

Joining Technique:	**Laser CO2 welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Laser CO2 welding.			
Investment cost:	**568.045 EURO**		**per seam:**	**0,01459 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1469 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Elect. welding transformer	6KW/57%	6	0,047 €	0,28 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	480	0,00003 €	0,01 €
- Lasergas He, N2, CO2		1	0,005 €	0,005 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 18000 m	0,03034	255,60 €	7,75 €
- Lense	1 per 180000 m	0,0036	30,70 €	0,11 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**12,66 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**568.045 €**	21,37 €
Sum manufacturing cost per hour with depreciation:				**34,03 €**
Example: 1000mm joining length (20 seams à 20mm/ seams distance 30mm)				
- Joining time:	28 sec			
- Robot time:	16 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	49 sec	(1469 seams/hour)	**per seam:**	**0,02316 €/seam**

Table 7.7.1: JT cost template for JT Laser CO_2 welding, steel-steel.

Joining Technique:	**Laser CO_2 welding**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Laser CO_2 welding.			
Investment cost:	**568.045 EURO**		**per seam:**	**0,01488 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1440 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	7,6	0,047 €	0,36 €
- Elect. welding transformer	6KW/57%	6	0,047 €	0,28 €
- Electricity for turntable	4 KWh/%	4,1	0,047 €	0,19 €
- Cooling water	2 bar/ 4ltr. per min.	510	0,00003 €	0,02 €
- Lasergas He, N2, CO2		1	0,005 €	0,005 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 14000 m	0,04034	255,60 €	10,31 €
- Lense	1 per 170000 m	0,0066	30,70 €	0,20 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**15,45 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**568.045 €**	21,37 €
Sum manufacturing cost per hour with depreciation:				**36,82 €**
Example: 1000mm joining length (20 seams à 20mm/ seams distance 30mm)				
- Joining time:	29 sec			
- Robot time:	16 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	50 sec	(1440 seams/hour)	**per seam:**	**0,02556 €/seam**

Table 7.7.2: JT cost template for JT Laser CO_2 welding, steel-high tensile steel.

Joining Technique:	**Laser CO_2 welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Laser CO_2welding.			
Investment cost:	**568.045 EURO**		**per seam:**	**0,01519 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1411 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Elect. welding transformer	6KW/57%	6	0,047 €	0,28 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	480	0,00003 €	0,01 €
- Lasergas He, N2, CO2		1	0,005 €	0,005 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 16000 m	0,03124	255,60 €	7,98 €
- Lense	1 per 160000 m	0,0136	30,70 €	0,42 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**13,19 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**568.045 €**	21,37 €
Sum manufacturing cost per hour with depreciation:				**34,56 €**
Example: 1000mm joining length (20 seams à 20mm/ seams distance 30mm)				
- Joining time:	30 sec			
- Robot time:	16 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	51 sec	(1411 seams/hour)	**per seam:**	**0,02449 €/seam**

Table 7.7.3: JT cost template for JT Laser CO_2 welding, aluminium-aluminium.

7.8 Laser diodes welding

Joining Technique:	**Laser diodes welding**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Laser diodes welding.			
Investment cost:	**447.380 EURO**		**per seam:**	**0,015236 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1108 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Elect. welding transformer	70KW/57%	30,06	0,047 €	1,41 €
- Electricity for turntable	4 KWh/59%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 2ltr. per min.	114	0,00005 €	0,01 €
- Inert gas	Helium	1030	0,0050	5,150 €
- Compressed air	6 bar/ litre	7725	0,0001	0,3863 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 20000 m	0,02657	255,60 €	6,79 €
- Lense	1 per 180000 m	0,0087	30,70 €	0,27 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**18,12 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**447.380 €**	16,83 €
Sum manufacturing cost per hour with depreciation:				**34,95 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	31 sec			
- Robot time:	29 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	65 sec	(1108 seams/hour)	**per seam:**	**0,03154 €/seam**

Table 7.8.1: JT cost template for JT Laser diodes welding, steel-steel.

Joining Technique:	**Laser diodes welding**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Laser diodes welding.			
Investment cost:	**447.380 EURO**		**per seam:**	**0,015941 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1059 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,9	0,047 €	0,32 €
- Elect. welding transformer	70KW/57%	30,06	0,047 €	1,41 €
- Electricity for turntable	4 KWh/59%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 2ltr. per min.	114	0,00005 €	0,01 €
- Inert gas	Helium	1120	0,0050	5,600 €
- Compressed air	6 bar/ litre	7725	0,0001	0,3863 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 20000 m	0,02657	255,60 €	6,79 €
- Lense	1 per 180000 m	0,0187	30,70 €	0,57 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**18,89 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**447.380 €**	16,83 €
Sum manufacturing cost per hour with depreciation:				**35,72 €**
Example: 1000mm joining length (20 seams à 25mm/ seams distance 25mm)				
- Joining time:	34 sec			
- Robot time:	29 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	68 sec	(1059 seams/hour)	**per seam:**	**0,033729 €/seam**

Table 7.8.2: JT cost template for JT Laser diodes welding, steel-high tensile steel.

Joining Technique:	Laser diodes welding		Aluminium - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Laser diodes welding.			
Investment cost:	447.380 EURO		per seam:	0,016882 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1000 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Elect. welding transformer	70KW/57%	30,06	0,047 €	1,41 €
- Electricity for turntable	4 KWh/59%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 2ltr. per min.	134	0,00005 €	0,01 €
- Inert gas	Helium	1130	0,0050	5,650 €
- Compressed air	6 bar/ litre	7725	0,0001	0,3863 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 20000 m	0,02757	255,60 €	7,05 €
- Lense	1 per 180000 m	0,167	30,70 €	5,13 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**22,71 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**447.380 €**	16,83 €
Sum manufacturing cost per hour with depreciation:				**39,54 €**
Example: **1000mm joining length (20 seams à 25mm/ seams distance 25mm)**				
- Joining time:	38 sec			
- Robot time:	29 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	72 sec	(1000 seams/hour)	per seam:	0,03954 €/seam

Table 7.8.3: JT cost template for JT Laser diodes welding, aluminium-aluminium.

7.9 Laser YAG welding

Joining Technique:	Laser YAG welding		Steel - Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Laser YAG welding.			
Investment cost:	672.331 EURO		per seam:	0,008105 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 3130 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Electricity Laser welding	220KVA	210	0,047 €	9,87 €
- Electricity cooling device	34KWh	20	0,047 €	0,94 €
- Electricity for turntable	4 KWh/59%	3,2	0,047 €	0,15 €
- Cooling water	33m³/h	33	0,00005 €	0,0017 €
- Inert gas	Helium 15litre/min	632	0,0050	3,160 €
- Compressed air	6 bar/150 litre p. minute	8400	0,0001	0,4200 €
- Compressed Crossjet	6 bar/150 litre p. minute	7200	0,0001	0,3600 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 10000 seams	0,02657	255,00 €	6,78 €
- Flashlight		0,00032	3.400,00 €	1,09 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**27,16 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**672.331 €**	25,29 €
Sum manufacturing cost per hour with depreciation:				**52,45 €**
Example: **1000mm joining length (20 seams à 35mm/ seams distance 15mm)**				
- Joining time:	8 sec			
- Robot time:	10 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	23 sec	(3130 seams/hour)	per seam:	0,016757 €/seam

Table 7.9.1: JT cost template for JT Laser YAG welding, steel-steel.

Joining Technique:	**Laser YAG welding**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Laser YAG welding.			
Investment cost:	**672.331 EURO**		**per seam:**	**0,012333 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 2057 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Electricity Laser welding	220KVA	320	0,047 €	15,04 €
- Electricity cooling device	34KWh	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/59%	3,2	0,047 €	0,15 €
- Cooling water	33m³/h	33	0,00005 €	0,0017 €
- Inert gas	Helium 15litre/min	736	0,0050	3,680 €
- Compressed air	6 bar/150 litre p. minute	8400	0,0001	0,4200 €
- Compressed Crossjet	6 bar/150 litre p. minute	7200	0,0001	0,3600 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 10000 seams	0,02657	255,00 €	6,78 €
- Flashlight		0,00032	3.400,00 €	1,09 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**33,08 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**672.331 €**	25,29 €
Sum manufacturing cost per hour with depreciation:				**58,37 €**
Example: 1000mm joining length (20 seams à 35mm/ seams distance 15mm)				
- Joining time:	14 sec			
- Robot time:	16 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	35 sec	(2057 seams/hour)	**per seam:**	**0,028376 €/seam**

Table 7.9.2: JT cost template for JT Laser YAG welding, steel-high tensile steel.

Joining Technique:	**Laser YAG welding**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Laser YAG welding.			
Investment cost:	**672.331 EURO**		**per seam:**	**0,010221 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 2482 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6,6	0,047 €	0,31 €
- Electricity Laser welding	220KVA	210	0,047 €	9,87 €
- Electricity cooling device	34KWh	30	0,047 €	1,41 €
- Electricity for turntable	4 KWh/59%	3,2	0,047 €	0,15 €
- Cooling water	33m³/h	33	0,00005 €	0,0017 €
- Inert gas	Helium 15litre/min	652	0,0050	3,260 €
- Compressed air	6 bar/150 litre p. minute	7200	0,0001	0,3600 €
- Compressed Crossjet	6 bar/150 litre p. minute	7200	0,0001	0,3600 €
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 10000 seams	0,02757	255,00 €	7,03 €
- Flashlight		0,00032	3.400,00 €	1,09 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**25,88 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**672.331 €**	25,29 €
Sum manufacturing cost per hour with depreciation:				**51,17 €**
Example: 1000mm joining length (20 seams à 35mm/ seams distance 15mm)				
- Joining time:	11 sec			
- Robot time:	13 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	29 sec	(2482 seams/hour)	**per seam:**	**0,020616 €/seam**

Table 7.9.3: JT cost template for JT Laser YAG welding, aluminium-aluminium.

7.10 Projection welding

Joining Technique:	Projection welding		Steel - Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Projection welding.			
Investment cost:	223.059 EURO		per spot:	0,006545 €/spot
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1286 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 3000 spots	0,2304	0,51 €	0,12 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	12	0,047 €	0,56 €
- Electricity for welding transformer	0,018 kwh/spot	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 6ltr. per min.	340	0,00005 €	0,02 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,0121	256,46 €	3,10 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	1	1,02 €	1,02 €
Sum manufacturing cost per hour without depreciation:				**6,86 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**223.059 €**	8,59 €
Sum manufacturing cost per hour with depreciation:				**15,45 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	46 sec			
- Robot time:	5 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	56 sec	(1286 spots/hour)	per spot:	0,01201 €/spot

Table 7.10.1: JT cost template for JT projection welding, steel-steel.

Joining Technique:	Projection welding		Steel - High tensile steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Projection welding.			
Investment cost:	223.059 EURO		per spot:	0,006782 €/spot
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1241 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 2500 spots	0,3404	0,51 €	0,17 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	15	0,047 €	0,71 €
- Electricity for welding transformer	0,018 kwh/spot	27	0,047 €	1,27 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 6ltr. per min.	390	0,00005 €	0,02 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	3224	0,00005 €	0,16 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,0159	256,46 €	4,08 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	1	1,02 €	1,02 €
Sum manufacturing cost per hour without depreciation:				**8,15 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**223.059 €**	8,59 €
Sum manufacturing cost per hour with depreciation:				**16,74 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	48 sec			
- Robot time:	5 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	58 sec	(1241 spots/hour)	per spot:	0,01348 €/spot

Table 7.10.2: JT cost template for JT projection welding, steel-high tensile steel.

7.11 Laser brazing

Joining Technique:	**Laser brazing**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Laser brazing.			
Investment cost:	**528.045 EURO**		**per seam:**	**0,02047 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 973 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	CuSi3/ 0,9mm	0,899	8,37 €	7,52 €
- Bolts		517x1,74g = 899,6g		
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	4,6	0,047 €	0,22 €
- Elect. welding transformer	6KW/57%	6	0,047 €	0,28 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	490	0,00003 €	0,01 €
- Lasergas He, N2, CO2		1	0,005 €	0,005 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 32000 m	0,01034	255,60 €	2,64 €
- Lense	1 per 180000 m	0,0036	30,70 €	0,11 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**7,45 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**528.045 €**	20,11 €
Sum manufacturing cost per hour with depreciation:				**27,56 €**
Example: 1000mm joining length (20 seams à 30mm/ seams distance 20mm)				
- Joining time:	58 sec			
- Robot time:	11 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	74 sec	(973 seams/hour)	**per seam:**	**0,02832 €/seam**

Table 7.11.1: JT cost template for JT laser brazing, steel-steel.

Joining Technique:	**Laser brazing**		**Steel - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium**, by utilisation of Laser brazing.			
Investment cost:	**528.045 EURO**		**per seam:**	**0,02075 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 960 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	S-AlSi5/ 1,2mm	0,934	8,00 €	7,47 €
- Bolts		537x1,74g = 934,3g		
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	4,9	0,047 €	0,23 €
- Elect. welding transformer	6KW/57%	12	0,047 €	0,56 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	539	0,00003 €	0,02 €
- Lasergas He, N2, CO2		3	0,005 €	0,015 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 32000 m	0,01024	255,60 €	2,62 €
- Lense	1 per 180000 m	0,0036	30,70 €	0,11 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**7,73 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**528.045 €**	20,11 €
Sum manufacturing cost per hour with depreciation:				**27,84 €**
Example: 1000mm joining length (20 seams à 30mm/ seams distance 20mm)				
- Joining time:	59 sec			
- Robot time:	11 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	75 sec	(960 seams/hour)	**per seam:**	**0,029 €/seam**

Table 7.11.2: JT cost template for JT laser brazing, steel-aluminium.

Joining Technique:	**Laser brazing**		**Aluminium - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel**, by utilisation of Laser brazing.			
Investment cost:	**528.045 EURO**		**per seam:**	**0,02131 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 935 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	S-AlSi5/ 1,2mm	0,95	8,00 €	7,60 €
- Bolts		546x1,74g = 950,1g		
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	4,9	0,047 €	0,23 €
- Elect. welding transformer	6KW/57%	14	0,047 €	0,66 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water	2 bar/ 4ltr. per min.	539	0,00003 €	0,02 €
- Lasergas He, N2, CO2		3	0,005 €	0,015 €
- Compressed air				
Maintenance:				
a) Material				
- Protection glass Crossjet	1 per 30000 m	0,01074	255,60 €	2,75 €
- Lense	1 per 180000 m	0,0036	30,70 €	0,11 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**7,95 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**528.045 €**	20,11 €
Sum manufacturing cost per hour with depreciation:				**28,06 €**
Example: 1000mm joining length (20 seams à 30mm/ seams distance 20mm)				
- Joining time:	61 sec			
- Robot time:	11 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	77 sec	(935 seams/hour)	**per seam:**	**0,03001 €/seam**

Table 7.11.3: JT cost template for JT laser brazing, aluminium-high tensile steel.

7.12 MAG brazing

Joining Technique:	**MAG brazing**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of MAG brazing.			
Investment cost:	**184.069 EURO**		**per seam:**	**0,00646 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1074 seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire	CuSi3/ 1,0mm	0,9349	7,00 €	6,54 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/52%	6	0,047 €	0,28 €
- Elect. welding transformer	10KW/57%	3,6	0,047 €	0,17 €
- Electricity for turntable	4 KWh/%	2,1	0,047 €	0,10 €
- Cooling water				
- Inert gas				
- Compressed air				
Maintenance:				
a) Material				
- Contact pipe	1 per 1200 seams	0,2633	0,59 €	0,16 €
- Gas nozzle	1 per 10000 seams	0,3297	6,14 €	2,02 €
- Brass core	1 per 50000 seams	0,0698	6,49 €	0,45 €
- Splash guard	1 per 10000 seams	0,1374	2,56 €	0,35 €
- Wire core	1 per 25000 seams	0,2868	13,34 €	3,83 €
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**17,98 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**184.069 €**	6,92 €
Sum manufacturing cost per hour with depreciation:				**24,90 €**
Example: 1000mm joining length (20 seams à 30mm/ seams distance 20mm)				
- Joining time:	50 sec			
- Robot time:	12 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	67 sec	(1074 seams/hour)	**per seam:**	**0,02318 €/seam**

Table 7.12.1: JT cost template for JT MAG brazing, steel-steel.

7.13 Punch riveting

Joining Technique:	Punch riveting		Steel - Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Punch riveting.			
Investment cost:	227.526 EURO		per rivet:	0,007876 €/rivet
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1090 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	1055	0,01 €	10,55 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,6	0,047 €	0,31 €
- Electricity for riveting gun	0,018 kwh/rivet	19	0,047 €	0,89 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	6859	0,00005 €	0,34 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 2mill. rivets	0,01036	196,34 €	2,03 €
- Tube, punch	1 kit per 1mill. rivets	0,0178	168,70 €	3,00 €
- Punching tool	1 kit per 0,6mill. rivets	0,0932	53,00 €	4,94 €
- Compact spring	1 piece per 1,3mill. rivets	0,003029	373,24 €	1,13 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**25,36 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**227.529 €**	8,56 €
Sum manufacturing cost per hour with depreciation:				**33,92 €**
Example: 1000mm joining length (20 rivets/ rivet distance 50mm)				
- Joining time:	59 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	66 sec	(1090 rivets/hour)	**per rivet:**	**0,03111 €/rivet**

Table 7.13.1: JT cost template for JT punch riveting, steel-steel.

Joining Technique:	Punch riveting		Steel - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium**, by utilisation of Punch riveting.			
Investment cost:	227.526 EURO		per rivet:	0,007994 €/rivet
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1074 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	1055	0,01 €	10,55 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,1	0,047 €	0,29 €
- Electricity for riveting gun	0,018 kwh/rivet	21	0,047 €	0,99 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	6959	0,00005 €	0,35 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 2mill. rivets	0,0196	196,34 €	3,85 €
- Tube, punch	1 kit per 1mill. rivets	0,0198	168,70 €	3,34 €
- Punching tool	1 kit per 0,6mill. rivets	0,0992	53,00 €	5,26 €
- Compact spring	1 piece per 1,3mill. rivets	0,00329	373,24 €	1,23 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**28,00 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**227.529 €**	8,56 €
Sum manufacturing cost per hour with depreciation:				**36,56 €**
Example: 1000mm joining length (20 rivets/ rivet distance 50mm)				
- Joining time:	60 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	67 sec	(1074 rivets/hour)	**per rivet:**	**0,03404 €/rivet**

Table 7.13.2: JT cost template for JT punch riveting, steel-aluminium.

Joining Technique:	Punch riveting		Aluminium - High tensile steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel**, by utilisation of Punch riveting.			
Investment cost:	227.526 EURO		per rivet:	0,008467 €/rivet
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1014 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	1055	0,01 €	10,55 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	9,1	0,047 €	0,43 €
- Electricity for riveting gun	0,018 kwh/rivet	32	0,047 €	1,50 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	7659	0,00005 €	0,38 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 1,6mill. rivets	0,0276	196,34 €	5,42 €
- Tube, punch	1 kit per 0,9mill. rivets	0,0248	168,70 €	4,18 €
- Punching tool	1 kit per 0,6mill. rivets	0,0992	53,00 €	5,26 €
- Compact spring	1 piece per 1,1mill. rivets	0,00379	373,24 €	1,41 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**31,30 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**227.529 €**	8,56 €
Sum manufacturing cost per hour with depreciation:				**39,86 €**
Example: 1000mm joining length (20 rivets/ rivet distance 50mm)				
- Joining time:	64 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	71 sec	(1014 rivets/hour)	per rivet:	0,039309 €/rivet

Table 7.13.3: JT cost template for JT punch riveting, aluminium-high tensile steel.

Joining Technique:	Punch riveting		Aluminium - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Punch riveting.			
Investment cost:	227.526 EURO		per rivet:	0,008115 €/rivet
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1058 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	1055	0,01 €	10,55 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	7,6	0,047 €	0,36 €
- Electricity for riveting gun	0,018 kwh/rivet	23	0,047 €	1,08 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	6989	0,00005 €	0,35 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 1,5 mill. rivets	0,01136	196,34 €	2,23 €
- Tube, punch	1 kit per 1mill. rivets	0,018	168,70 €	3,04 €
- Punching tool	1 kit per 0,5mill. rivets	0,0992	53,00 €	5,26 €
- Compact spring	1 piece per 1,1mill. rivets	0,0039	373,24 €	1,46 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**26,48 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**227.529 €**	8,56 €
Sum manufacturing cost per hour with depreciation:				**35,04 €**
Example: 1000mm joining length (20 rivets/ rivet distance 50mm)				
- Joining time:	61 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	68 sec	(1058 rivets/hour)	per rivet:	0,033119 €/rivet

Table 7.13.4: JT cost template for JT punch riveting, aluminium-aluminium.

7.14 Blind riveting

Joining Technique:	**Blind riveting**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Blind riveting.			
Investment cost:	**233.661 EURO**		**per rivet:**	**0,011147 €/rivet**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 791 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	791	0,01 €	7,91 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,9	0,047 €	0,32 €
- Electricity for riveting gun	0,018 kwh/rivet	29	0,047 €	1,36 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air				
Maintenance:				
a) Material				
- Tool kit	1 kit per 1,9mill. rivets	0,0413	104,30 €	4,31 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**16,06 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**233.661 €**	8,79 €
Sum manufacturing cost per hour with depreciation:				**24,85 €**
Example: **1000mm joining length (20 blindrivets / rivet distance 50mm)**				
- Joining time:	60 sec			
- Robot time:	26 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	91 sec	(791 rivets/hour)	**per rivet:**	**0,031415 €/rivet**

Table 7.14.1: JT cost template for JT blind riveting, steel-steel.

Joining Technique:	**Blind riveting**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Blind riveting.			
Investment cost:	**233.661 EURO**		**per rivet:**	**0,012489 €/rivet**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 706 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	791	0,01 €	7,91 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,9	0,047 €	0,32 €
- Electricity for riveting gun	0,018 kwh/rivet	46	0,047 €	2,16 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	7959	0,00005 €	0,40 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 1,8mill. rivets	0,0413	104,30 €	4,31 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**17,26 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**233.661 €**	8,79 €
Sum manufacturing cost per hour with depreciation:				**26,05 €**
Example: **1000mm joining length (20 blindrivets/ rivet distance 50mm)**				
- Joining time:	71 sec			
- Robot time:	26 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	102 sec	(706 rivets/hour)	**per rivet:**	**0,036898 €/rivet**

Table 7.14.2: JT cost template for JT blind riveting, steel-high tensile steel.

Joining Technique:	**Blind riveting**		**Steel - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium,** by utilisation of Blind riveting.			
Investment cost:	**233.661 EURO**		**per rivet:**	**0,012012 €/rivet**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 734 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	791	0,01 €	7,91 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,9	0,047 €	0,32 €
- Electricity for riveting gun	0,018 kwh/rivet	41	0,047 €	1,93 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	7659	0,00005 €	0,38 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 2mill. rivets	0,0413	104,30 €	4,31 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**17,01 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**233.661 €**	8,79 €
Sum manufacturing cost per hour with depreciation:				**25,80 €**
Example: 1000mm joining length (20 blindrivets/ rivet distance 50mm)				
- Joining time:	67 sec			
- Robot time:	26 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	98 sec	(734 rivets/hour)	**per rivet:**	**0,035149 €/rivet**

Table 7.14.3: JT cost template for JT blind riveting, steel-aluminium.

Joining Technique:	**Blind riveting**		**Aluminium - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel,** by utilisation of Blind riveting.			
Investment cost:	**233.661 EURO**		**per rivet:**	**0,011756 €/rivet**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 750 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	791	0,01 €	7,91 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	7,6	0,047 €	0,36 €
- Electricity for riveting gun	0,018 kwh/rivet	48	0,047 €	2,26 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	8359	0,00005 €	0,42 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 2,2mill. rivets	0,0413	104,30 €	4,31 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**17,41 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**233.661 €**	8,79 €
Sum manufacturing cost per hour with depreciation:				**26,20 €**
Example: 1000mm joining length (20 blindrivets/ rivet distance 50mm)				
- Joining time:	65 sec			
- Robot time:	26 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	96 sec	(750 rivets/hour)	**per rivet:**	**0,034933 €/rivet**

Table 7.14.4: JT cost template for JT blind riveting, aluminium-high tensile steel.

Joining Technique:	**Blind riveting**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Blind riveting.			
Investment cost:	**233.661 EURO**		**per rivet:**	**0,011147 €/rivet**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 791 rivets/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet	pieces	791	0,01 €	7,91 €
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,5	0,047 €	0,31 €
- Electricity for riveting gun	0,018 kwh/rivet	25	0,047 €	1,18 €
- Electricity for turntable	4 KWh/%	2,5	0,047 €	0,12 €
- Cooling water				
- Inert gas				
- Compressed air	6 bar/ 6,5 ltr. per rivet	7359	0,00005 €	0,37 €
Maintenance:				
a) Material				
- Tool kit	1 kit per 2mill. rivets	0,0423	104,30 €	4,41 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**16,33 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**233.661 €**	8,79 €
Sum manufacturing cost per hour with depreciation:				**25,12 €**
Example: 1000mm joining length (20 blindrivets / rivet distance 50mm)				
- Joining time:	60 sec			
- Robot time:	26 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	91 sec	(791 rivets/hour)	**per rivet:**	**0,031757 €/rivet**

Table 7.14.5: JT cost template for JT blind riveting, aluminium-aluminium.

7.15 Clinching

Joining Technique:	**Clinching**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Clinching.			
Investment cost:	**191.227 EURO**		**per clinch:**	**0,006712 €/clinch**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1075 clinchs/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,6975	9,2033 €	6,42 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,6	0,047 €	0,31 €
- Electricity for clinching gun	10 KW/rivet	9	0,047 €	0,42 €
- Electricity for turntable	4 KWh/%	2	0,047 €	0,09 €
- Cooling water	l/h	60	0,0003 €	0,02 €
- Temperature device	2,25 KW/%	28	0,0470 €	1,32 €
- Compressed air	6 bar/6,5 NL per clinch	6985	0,0001 €	0,35 €
Maintenance:				
a) Material				
- Punch	1 piece per 200000	0,004973	46,02 €	0,23 €
- Clinching tool	1 piece per 200000	0,00425	148,28 €	0,63 €
- Holder	1 piece per 200000	0,0117	15,34 €	0,18 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**12,01 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**191.227 €**	7,19 €
Sum manufacturing cost per hour with depreciation:				**19,20 €**
Example: 1000mm joining length (20 clinchs / clinch distance 50mm)				
- Joining time:	60 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	67 sec	(1075 clinchs/hour)	**per clinch:**	**0,01786 €/clinch**

Table 7.15.1: JT cost template for JT clinching, steel-steel.

Joining Technique:	**Clinching**		**Steel - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium**, by utilisation of Clinching.			
Investment cost:	**191.227 EURO**		**per clinch:**	**0,007717 €/clinch**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 935 clinchs/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,6975	9,2033 €	6,42 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,6	0,047 €	0,31 €
- Electricity for clinching gun	10 KW/rivet	8,8	0,047 €	0,41 €
- Electricity for turntable	4 KWh/%	2	0,047 €	0,09 €
- Cooling water	l/h	67	0,0003 €	0,02 €
- Temperature device	2,25 KW/%	26,1	0,0470 €	1,23 €
- Compressed air	6 bar/6,5 NL per clinch	7485	0,0001 €	0,37 €
Maintenance:				
a) Material				
- Punch	1 piece per 170000	0,005573	46,02 €	0,26 €
- Clinching tool	1 piece per 150000	0,00825	148,28 €	1,22 €
- Holder	1 piece per 200000	0,0117	15,34 €	0,18 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**12,56 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**191.227 €**	7,19 €
Sum manufacturing cost per hour with depreciation:				**19,75 €**
Example: **1000mm joining length (20 clinchs / clinch distance 50mm)**				
- Joining time:	70 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	77 sec	(935 clinchs/hour)	**per clinch:**	**0,021122 €/clinch**

Table 7.15.2: JT cost template for JT clinching, steel-aluminium.

Joining Technique:	**Clinching**		**Aluminium - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel**, by utilisation of Clinching.			
Investment cost:	**191.227 EURO**		**per clinch:**	**0,008323 €/clinch**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 867 clinchs/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,7075	9,2033 €	6,51 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	7,2	0,047 €	0,34 €
- Electricity for clinching gun	10 KW/rivet	13,8	0,047 €	0,65 €
- Electricity for turntable	4 KWh/%	2	0,047 €	0,09 €
- Cooling water	l/h	56	0,0003 €	0,02 €
- Temperature device	2,25 KW/%	17	0,0470 €	0,80 €
- Compressed air	6 bar/6,5 NL per clinch	8185	0,0001 €	0,41 €
Maintenance:				
a) Material				
- Punch	1 piece per 150000	0,009653	46,02 €	0,44 €
- Clinching tool	1 piece per 130000	0,01825	148,28 €	2,71 €
- Holder	1 piece per 200000	0,0117	15,34 €	0,18 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**14,19 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**191.227 €**	7,19 €
Sum manufacturing cost per hour with depreciation:				**21,38 €**
Example: **1000mm joining length (20 clinchs / clinch distance 50mm)**				
- Joining time:	76 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	83 sec	(867 clinchs/hour)	**per clinch:**	**0,024659 €/clinch**

Table 7.15.3: JT cost template for JT clinching, aluminium-high tensile steel.

Joining Technique:	Clinching		Aluminium - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Clinching.			
Investment cost:	191.227 EURO		per clinch:	0,006512 €/clinch
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1108 clinchs/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,6375	9,2033 €	5,87 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6,4	0,047 €	0,30 €
- Electricity for clinching gun	10 KW/rivet	9,4	0,047 €	0,44 €
- Electricity for turntable	4 KWh/%	2	0,047 €	0,09 €
- Cooling water	l/h	56	0,0003 €	0,02 €
- Temperature device	2,25 KW/%	21	0,0470 €	0,99 €
- Compressed air	6 bar/6,5 NL per clinch	6665	0,0001 €	0,33 €
Maintenance:				
a) Material				
- Punch	1 piece per 180000	0,005773	46,02 €	0,27 €
- Clinching tool	1 piece per 200000	0,00425	148,28 €	0,63 €
- Holder	1 piece per 200000	0,0117	15,34 €	0,18 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**11,16 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**191.227 €**	7,19 €
Sum manufacturing cost per hour with depreciation:				**18,35 €**
Example: 1000mm joining length (20 clinchs / clinch distance 50mm)				
- Joining time:	68 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	65 sec	(1108 clinchs/hour)	per clinch:	0,016561 €/clinch

Table 7.15.4: JT cost template for JT clinching, aluminium-aluminium.

7.16 Flanging

Joining Technique:	Flanging		Steel - Steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Flanging.			
Investment cost:	688.203 EURO		per seam:	0,018405 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1411 flanging seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,72	9,2030 €	6,63 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for flanging device	6,6 KVA/%	6,6	0,047 €	0,31 €
- Electricity for robot	10 KW/rivet	5	0,047 €	0,24 €
- Electricity for gluing gun	4 KWh/%	3,6	0,047 €	0,17 €
- Electricity for inductive curing	25KVA/%	24	0,047 €	1,13 €
- Cooling water	60l/h	60	0,0230 €	1,38 €
- Compressed air	10l/min	504	0,0001 €	0,03 €
Maintenance:				
a) Material				
- Flanging device rolls	1 piece per 80000m	0,004973	36,02 €	0,18 €
- Gluing kit	1 piece per 20000m	0,01925	48,28 €	0,93 €
- Robot D33				
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**15,06 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**668.203 €**	25,89 €
Sum manufacturing cost per hour with depreciation:				**40,95 €**
Example: 1000mm joining length (20 flanging seams à 50mm)				
- Joining time:	45 sec			
- Robot time:	1 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	51 sec	(1411 seams/hour)	per seam:	0,029021 €/seam

Table 7.16.1: JT cost template for JT flanging, steel-steel.

Joining Technique:	**Flanging**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Flanging.			
Investment cost:	**688.203 EURO**		**per seam:**	**0,020926 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1241 flanging seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,79	9,2030 €	7,27 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for flanging device	6,6 KVA/%	8,2	0,047 €	0,39 €
- Electricity for robot	10 KW/rivet	5	0,047 €	0,24 €
- Electricity for gluing gun	4 KWh/%	3,8	0,047 €	0,18 €
- Electricity for inductive curing	25KVA/%	29	0,047 €	1,36 €
- Cooling water	60l/h	65	0,0230 €	1,50 €
- Compressed air	10l/min	504	0,0001 €	0,03 €
Maintenance:				
a) Material				
- Flanging device rolls	1 piece per 60000m	0,01973	36,02 €	0,71 €
- Gluing kit	1 piece per 20000m	0,01925	48,28 €	0,93 €
- Robot D33				
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**16,67 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**668.203 €**	25,89 €
Sum manufacturing cost per hour with depreciation:				**42,56 €**
Example: **1000mm joining length (20 flanging seams à 50mm)**				
- Joining time:	52 sec			
- Robot time:	1 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	58 sec	(1241 seams/hour)	**per seam:**	**0,034294 €/seam**

Table 7.16.2: JT cost template for JT flanging, steel-high tensile steel.

Joining Technique:	**Flanging**		**Steel - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium**, by utilisation of Flanging.			
Investment cost:	**688.203 EURO**		**per seam:**	**0,019123 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1358 flanging seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,81	9,2030 €	7,45 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for flanging device	6,6 KVA/%	7,2	0,047 €	0,34 €
- Electricity for robot	10 KW/rivet	5	0,047 €	0,24 €
- Electricity for gluing gun	4 KWh/%	3,4	0,047 €	0,16 €
- Electricity for inductive curing	25KVA/%	23,4	0,047 €	1,10 €
- Cooling water	60l/h	60	0,0230 €	1,38 €
- Compressed air	10l/min	484	0,0001 €	0,02 €
Maintenance:				
a) Material				
- Flanging device rolls	1 piece per 100000m	0,01473	36,02 €	0,53 €
- Gluing kit	1 piece per 50000m	0,01625	48,28 €	0,78 €
- Robot D33				
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**16,09 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**668.203 €**	25,89 €
Sum manufacturing cost per hour with depreciation:				**41,98 €**
Example: **1000mm joining length (20 flanging seams à 50mm)**				
- Joining time:	47 sec			
- Robot time:	1 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	53 sec	(1358 seams/hour)	**per seam:**	**0,030913 €/seam**

Table 7.16.3: JT cost template for JT flanging, steel-aluminium.

Joining Technique:	**Flanging**		**Aluminium - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel**, by utilisation of Flanging.			
Investment cost:	**688.203 EURO**		**per seam:**	**0,020562 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1263 flanging seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,83	9,2030 €	7,64 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for flanging device	6,6 KVA/%	9,2	0,047 €	0,43 €
- Electricity for robot	10 KW/rivet	5	0,047 €	0,24 €
- Electricity for gluing gun	4 KWh/%	4,3	0,047 €	0,20 €
- Electricity for inductive curing	25KVA/%	31	0,047 €	1,46 €
- Cooling water	60l/h	62	0,0230 €	1,43 €
- Compressed air	10l/min	532	0,0001 €	0,03 €
Maintenance:				
a) Material				
- Flanging device rolls	1 piece per 45000m	0,02473	36,02 €	0,89 €
- Gluing kit	1 piece per 25000m	0,01914	48,28 €	0,92 €
- Robot D33				
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**17,31 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**668.203 €**	25,89 €
Sum manufacturing cost per hour with depreciation:				**43,20 €**
Example: **1000mm joining length (20 flanging seams à 50mm)**				
- Joining time:	51 sec			
- Robot time:	1 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	57 sec	(1263 seams/hour)	**per seam:**	**0,034204 €/seam**

Table 7.16.4: JT cost template for JT flanging, aluminium-high tensile steel.

Joining Technique:	**Flanging**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Flanging.			
Investment cost:	**688.203 EURO**		**per seam:**	**0,018764 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1384 flanging seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate XW	0,72	9,2030 €	6,63 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for flanging device	6,6 KVA/%	6,6	0,047 €	0,31 €
- Electricity for robot	10 KW/rivet	5	0,047 €	0,24 €
- Electricity for gluing gun	4 KWh/%	3,6	0,047 €	0,17 €
- Electricity for inductive curing	25KVA/%	30	0,047 €	1,41 €
- Cooling water	60l/h	60	0,0230 €	1,38 €
- Compressed air	10l/min	504	0,0001 €	0,03 €
Maintenance:				
a) Material				
- Flanging device rolls	1 piece per 10000m	0,004473	36,02 €	0,16 €
- Gluing kit	1 piece per 40000m	0,01525	48,28 €	0,74 €
- Robot D33				
b) Labour	Minutes	4	1,02 €	4,08 €
Sum manufacturing cost per hour without depreciation:				**15,13 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**668.203 €**	25,89 €
Sum manufacturing cost per hour with depreciation:				**41,02 €**
Example: **1000mm joining length (20 flanging seams à 50mm)**				
- Joining time:	46 sec			
- Robot time:	1 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	52 sec	(1384 seams/hour)	**per seam:**	**0,029638 €/seam**

Table 7.16.5: JT cost template for JT flanging, aluminium-aluminium.

7.17 Cohesiveness gluing

Joining Technique:	**Cohesiveness gluing**		**Steel - Steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of Cohesivness gluing.			
Investment cost:	**1.329.359 EURO**		**per seam:**	**0,011147 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 4500 gluing seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate 1480	2,25	17,8950 €	40,26 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for gluing	2,0 KVA/%	2	0,047 €	0,09 €
- Electricity for glue-heating	2,25 KW/rivet	6	0,047 €	0,28 €
- Electricity for 2 robots	0,8 KWh/%	12	0,047 €	0,56 €
- Electricity for turn table	4 KW/%	4	0,047 €	0,19 €
- Electricity curing oven	250 KW/%	45	0,047 €	2,12 €
- Natural gas (oven)	20 m³/h	20	0,023 €	0,46 €
- Cooling zone	15 KW	15	0,0470 €	0,71 €
- Compressed air for barrel-pump	6 bar/litre	100	0,0001 €	0,01 €
Maintenance:				
a) Material				
- Diverse spare parts		1	1,00 €	1,00 €
- Clinchpoints	pieces	225	0,03 €	7,43 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**56,16 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.329.359 €**	50,01 €
Sum manufacturing cost per hour with depreciation:				**106,17 €**
Example: **1000mm joining length (20 gluing seams à 50mm/ 12-16mm width)**				
- Joining time:	8 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	16 sec	(4500 seams/hour)	**per seam:**	**0,023593 €/seam**

Table 7.17.1: JT cost template for JT cohesiveness gluing, steel-steel.

Joining Technique:	**Cohesiveness gluing**		**Steel - High tensile steel**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **high tensile steel**, by utilisation of Cohesivness gluing.			
Investment cost:	**1.329.359 EURO**		**per seam:**	**0,011845 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 4235 gluing seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate 1480	2,75	17,8950 €	49,21 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for gluing	2,0 KVA/%	2,3	0,047 €	0,11 €
- Electricity for glue-heating	2,25 KW/rivet	6,7	0,047 €	0,31 €
- Electricity for 2 robots	0,8 KWh/%	12	0,047 €	0,56 €
- Electricity for turn table	4 KW/%	4	0,047 €	0,19 €
- Electricity curing oven	250 KW/%	49	0,047 €	2,30 €
- Natural gas (oven)	20 m³/h	23	0,023 €	0,53 €
- Cooling zone	15 KW	17	0,0470 €	0,80 €
- Compressed air for barrel-pump	6 bar/litre	100	0,0001 €	0,01 €
Maintenance:				
a) Material				
- Diverse spare parts		1,3	1,00 €	1,30 €
- Clinchpoints	pieces	225	0,03 €	7,43 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**65,81 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.329.359 €**	50,01 €
Sum manufacturing cost per hour with depreciation:				**115,82 €**
Example: **1000mm joining length (20 gluing seams à 50mm/ 12-16mm width)**				
- Joining time:	9 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	17 sec	(4235 seams/hour)	**per seam:**	**0,027348 €/seam**

Table 7.17.2: JT cost template for JT cohesiveness gluing, steel-high tensile steel.

Joining Technique:	Cohesiveness gluing		Steel - Aluminium	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **steel** and one of **aluminium**, by utilisation of Cohesivness gluing.			
Investment cost:	1.329.359 EURO		per seam:	0,0125411 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 4000 gluing seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate 1480	2,79	17,8950 €	49,93 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for gluing	2,0 KVA/%	2,4	0,047 €	0,11 €
- Electricity for glue-heating	2,25 KW/rivet	6,9	0,047 €	0,32 €
- Electricity for 2 robots	0,8 KWh/%	12	0,047 €	0,56 €
- Electricity for turn table	4 KW/%	4	0,047 €	0,19 €
- Electricity curing oven	250 KW/%	49	0,047 €	2,30 €
- Natural gas (oven)	20 m³/h	26	0,023 €	0,60 €
- Cooling zone	15 KW	21	0,0470 €	0,99 €
- Compressed air for barrel-pump	6 bar/litre	100	0,0001 €	0,01 €
Maintenance:				
a) Material				
- Diverse spare parts		1,1	1,00 €	1,10 €
- Clinchpoints	pieces	225	0,03 €	7,43 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**66,59 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.329.359 €**	50,01 €
Sum manufacturing cost per hour with depreciation:				**116,60 €**
Example: 1000mm joining length (20 gluing seams à 50mm/ 12-16mm width)				
- Joining time:	10 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	18 sec	(4000 seams/hour)	per seam:	0,02915 €/seam

Table 7.17.3: JT cost template for JT cohesiveness gluing, steel-aluminium.

Joining Technique:	Cohesiveness gluing		Aluminium - High tensile steel	
Installation:	Flexibel manufacturing cell for the joining process of two 1000mm sheet components, one of **aluminium** and one of **high tensile steel**, by utilisation of Cohesivness gluing.			
Investment cost:	1.329.359 EURO		per seam:	0,011845 €/seam
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 4235 gluing seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate 1480	3,15	17,8950 €	56,37 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for gluing	2,0 KVA/%	2,7	0,047 €	0,13 €
- Electricity for glue-heating	2,25 KW/rivet	6,9	0,047 €	0,32 €
- Electricity for 2 robots	0,8 KWh/%	12	0,047 €	0,56 €
- Electricity for turn table	4 KW/%	4	0,047 €	0,19 €
- Electricity curing oven	250 KW/%	54	0,047 €	2,54 €
- Natural gas (oven)	20 m³/h	27	0,023 €	0,62 €
- Cooling zone	15 KW	25	0,0470 €	1,18 €
- Compressed air for barrel-pump	6 bar/litre	100	0,0001 €	0,01 €
Maintenance:				
a) Material				
- Diverse spare parts		1,1	1,00 €	1,10 €
- Clinchpoints	pieces	225	0,03 €	7,43 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**73,50 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.329.359 €**	50,01 €
Sum manufacturing cost per hour with depreciation:				**123,51 €**
Example: 1000mm joining length (20 gluing seams à 50mm/ 12-16mm width)				
- Joining time:	9 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		per Working Content:	
- Total cycle time:	17 sec	(4235 seams/hour)	per seam:	0,029164 €/seam

Table 7.17.4: JT cost template for JT cohesiveness gluing, aluminium-high tensile steel.

Joining Technique:	**Cohesiveness gluing**		**Aluminium - Aluminium**	
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **aluminium** sheet components by utilisation of Cohesivness gluing.			
Investment cost:	**1.329.359 EURO**		**per seam:**	**0,012541 €/seam**
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 4000 gluing seams/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Glue	10g/m Betamate 1480	3,2	17,8950 €	57,26 €
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes				
Electricity/water/air/gas:				
- Electricity for gluing	2,0 KVA/%	2,6	0,047 €	0,12 €
- Electricity for glue-heating	2,25 KW/rivet	6,7	0,047 €	0,31 €
- Electricity for 2 robots	0,8 KWh/%	12	0,047 €	0,56 €
- Electricity for turn table	4 KW/%	4	0,047 €	0,19 €
- Electricity curing oven	250 KW/%	55	0,047 €	2,59 €
- Natural gas (oven)	20 m³/h	35	0,023 €	0,81 €
- Cooling zone	15 KW	21	0,0470 €	0,99 €
- Compressed air for barrel-pump	6 bar/litre	100	0,0001 €	0,01 €
Maintenance:				
a) Material				
- Diverse spare parts		1,1	1,00 €	1,10 €
- Clinchpoints	pieces	225	0,03 €	7,43 €
b) Labour	Minutes	3	1,02 €	3,06 €
Sum manufacturing cost per hour without depreciation:				**74,42 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**1.329.359 €**	50,01 €
Sum manufacturing cost per hour with depreciation:				**124,43 €**
Example: 1000mm joining length (20 gluing seams à 50mm/ 12-16mm width)				
- Joining time:	10 sec			
- Robot time:	3 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	18 sec	(4000 seams/hour)	**per seam:**	**0,031107 €/seam**

Table 7.17.5: JT cost template for JT cohesiveness gluing, aluminium-aluminium.

8. Calculation of the Industrial Case Study

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Alu. - Alu.			Alu.-High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	Joining Tech. / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	0,005836	0,01642	1,25	--	--	--	0,006976	0,01613	1,50	--	--	--	0,00531	0,01137	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,05829	0,12421	1,50	--	--	--	0,04587	0,09774	1,25
3.	MIG welding	--	--	--	0,00685	0,01856	1,25	--	--	--	0,006659	0,019712	1,00	--	--	--	0,006274	0,016476	1,25
4.	Tandem MIG welding	--	--	--	0,00484	0,016917	1,25	--	--	--	0,005516	0,018699	1,25	--	--	--	0,004502	0,0156	1,25
5.	MAG welding	--	--	--	0,006792	0,01737	1,00	--	--	--	0,00794	0,02083	1,00	--	--	--	0,007307	0,01965	1,00
6.	WIG welding	--	--	--	0,00866	0,04032	1,00	--	--	--	--	--	--	--	--	--	0,008218	0,03844	1,00
7.	Laser-welding (CO_2)	--	--	--	0,01519	0,02449	1,25	--	--	--	0,01488	0,02556	1,25	--	--	--	0,01459	0,02316	1,25
8.	Laser-welding (Diodes)	--	--	--	0,016882	0,03954	1,25	--	--	--	0,01594	0,033729	1,25	--	--	--	0,01523	0,03154	1,25
9.	Laser-welding (YAG)	--	--	--	0,010221	0,020616	1,00	--	--	--	0,01233	0,02837	1,00	--	--	--	0,008105	0,016757	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,006782	0,01348	1,50	--	--	--	0,006545	0,01201	1,25
11.	Laser brazing	0,02075	0,029	1,00	--	--	--	0,02131	0,03001	1,25	--	--	--	0,02075	0,029	1,25	0,02047	0,02832	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,00646	0,02318	1,00
13.	Punch riveting	0,007994	0,03404	1,00	0,008115	0,033119	1,25	0,008467	0,039309	1,50	--	--	--	0,007994	0,03404	1,25	0,007876	0,03111	1,50
14.	Blind riveting	0,012012	0,035149	1,25	0,011147	0,031757	1,25	0,011756	0,034933	1,50	0,012489	0,036898	1,00	0,012012	0,035149	1,25	0,011147	0,031415	1,50
15.	Clinching	0,007717	0,021122	1,25	0,006512	0,016561	1,25	0,008323	0,024659	1,50	--	--	--	0,007717	0,021122	1,50	0,006712	0,01786	1,50
16.	Flanging	0,019123	0,030913	1,00	0,018764	0,029638	1,25	0,020562	0,034204	1,50	0,020926	0,034294	1,25	0,019123	0,030913	1,25	0,018405	0,029021	1,00
17.	Cohesiveness gluing	0,0125411	0,02915	1,25	0,012541	0,031107	1,25	0,011845	0,029164	1,25	0,011845	0,027348	1,25	0,0125411	0,02915	1,00	0,011147	0,023593	1,50

Figure 8.1: Starting Source matrix of Industrial Case Study.

8.1 Costs and SWC's calculation of the conventional JT Selection Procedure

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Aluminium - Aluminium			Alu. - High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	JT's / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	0,06566	0,18473	1,25	--	--	--	0,05232	0,12098	1,50	--	--	--	**0,03319**	**0,07106**	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,43718	0,93158	1,50	--	--	--	0,28669	0,61088	1,25
3.	MIG welding	--	--	--	**0,07706**	**0,20880**	1,25	--	--	--	0,03325	0,09856	1,00	--	--	--	0,03921	0,10298	1,25
4.	Tandem MIG welding	--	--	--	0,05445	0,19032	1,25	--	--	--	0,03448	0,11687	1,25	--	--	--	0,02814	0,09750	1,25
5.	MAG welding	--	--	--	0,06113	0,15633	1,00	--	--	--	**0,03970**	**0,10415**	1,00	--	--	--	0,03654	0,09825	1,00
6.	WIG welding	--	--	--	0,07794	0,36288	1,00	--	--	--	--	--	--	--	--	--	0,04109	0,19220	1,00
7.	Laser-welding (CO_2)	--	--	--	0,17089	0,27551	1,25	--	--	--	0,09300	0,15975	1,25	--	--	--	0,09119	0,14475	1,25
8.	Laser-welding (Diodes)	--	--	--	0,18992	0,44483	1,25	--	--	--	0,09963	0,21081	1,25	--	--	--	0,09519	0,19713	1,25
9.	Laser-welding (YAG)	--	--	--	0,09199	0,18554	1,00	--	--	--	0,06165	0,14185	1,00	--	--	--	0,04053	0,08379	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,05087	0,10110	1,50	--	--	--	0,04091	0,07506	1,25
11.	Laser brazing	0,08300	0,11600	1,00	--	--	--	**0,15983**	**0,22508**	1,25	--	--	--	0,08300	0,11600	1,00	0,12794	0,17700	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,03230	0,11590	1,00
13.	Punch riveting	**0,03198**	**0,13616**	1,00	0,09129	0,37259	1,25	0,07620	0,35378	1,50	--	--	--	**0,03997**	**0,17020**	1,25	0,05907	0,23333	1,50
14.	Blind riveting	0,06006	0,17575	1,25	0,12540	0,35727	1,25	0,10580	0,31440	1,50	0,06245	0,18449	1,00	0,06006	0,17575	1,25	0,08360	0,23561	1,50
15.	Clinching	0,03859	0,10561	1,25	0,07326	0,18631	1,25	0,07491	0,22193	1,50	--	--	--	0,04630	0,12673	1,50	0,05034	0,13395	1,50
16.	Flanging	0,07649	0,12365	1,00	0,21110	0,33343	1,25	0,18506	0,30784	1,50	0,13079	0,21434	1,25	0,09562	0,15457	1,25	0,09203	0,14511	1,00
17.	Cohesiveness gluing	0,06271	0,14575	1,25	0,14109	0,34995	1,25	0,08884	0,21873	1,25	0,07403	0,17093	1,25	0,05016	0,11660	1,00	0,06967	0,14746	1,25

Table 8.1.1: Source Matrix with marked JT allocation Solution for conventional JT Selection procedure.

JS number	1	2	3	4	5	6
Allocated JT number	13	3	11	5	13	1
Allocated JT	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding

Conventional Solution	1. Joining Side	2. Joining Side	3. Joining Side	4. Joining Side	5. Joining Side	6. Joining Side	Total cost per wheelhouse
Proposal Vector: [13, 3,11, 5, 13,1]	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding	
Manufacturing cost M per JS	0,13616	0,2088	0,22508	0,10415	0,1702	0,07106	0,91545
Investment cost c per JS	0,03198	0,07706	0,15983	0,0397	0,03997	0,03319	0,3817

JS number	1	2	3	4	5	6	Total number of SWC's
Ascertained JT Combination	Punch riveting	MIG welding	Laser brazing	MAG welding	Punch riveting	Spot welding	
JS Material Combination	Aluminium - Steel	Aluminium-Aluminium	Aluminium-High tensile steel	Steel-High tensile steel	Aluminium-Steel	Steel-Steel	
Number of WC	4	9	6	5	4	5	
SWCC	2,52002	1,52338	3,07674	1,72482	2,52002	1	
JSC	1,00	1,25	1,25	1,00	1,25	1,25	
Number of SWC's	10,08008	17,138025	23,07555	8,6241	12,6001	6,25	77,77

Table 8.1.2: JT solution vector, cost and SWC's solution table of conventional JT Selection procedure.

8.2 Costs and SWC's calculation of the optimal JT Selection Procedure

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Alu. - Alu.			Alu.-High tensile steel			Steel-High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	Joining Tech. / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	6,56550	18,47250	1,25	--	--	--	5,23200	12,09750	1,50	--	--	--	3,31875	7,10625	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	43,71750	93,15750	1,50	--	--	--	28,66875	61,08750	1,25
3.	MIG welding	--	--	--	7,70625	20,88000	1,25	--	--	--	3,32500	9,85600	1,00	--	--	--	3,92125	10,29750	1,25
4.	Tandem MIG welding	--	--	--	5,44500	19,03163	1,25	--	--	--	3,44750	11,68688	1,25	--	--	--	2,81375	9,75000	1,25
5.	MAG welding	--	--	--	6,11280	15,63300	1,00	--	--	--	3,97000	10,41500	1,00	--	--	--	3,65350	9,82500	1,00
6.	WIG welding	--	--	--	7,79400	36,28800	1,00	--	--	--	--	--	--	--	--	--	4,10900	19,22000	1,00
7.	Laser-welding (CO_2)	--	--	--	17,08875	27,55125	1,25	--	--	--	9,30000	15,97500	1,25	--	--	--	9,11875	14,47500	1,25
8.	Laser-welding (Diodes)	--	--	--	18,99225	44,48250	1,25	--	--	--	9,96250	21,08063	1,25	--	--	--	9,51875	19,71250	1,25
9.	Laser-welding (YAG)	--	--	--	9,19890	18,55440	1,00	--	--	--	6,16500	14,18500	1,00	--	--	--	4,05250	8,37850	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	5,08650	10,11000	1,50	--	--	--	4,09063	7,50625	1,25
11.	Laser brazing	8,30000	11,60000	1,00	--	--	--	15,98250	22,50750	1,25	--	--	--	8,30000	11,60000	1,00	12,79375	17,70000	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,23000	11,59000	1,00
13.	Punch riveting	3,19760	13,61600	1,00	9,12938	37,25888	1,25	7,62030	35,37810	1,50	--	--	--	3,99700	17,02000	1,25	5,90700	23,33250	1,50
14.	Blind riveting	6,00600	17,57450	1,25	12,54038	35,72663	1,25	10,58040	31,43970	1,50	6,24450	18,44900	1,00	6,00600	17,57450	1,25	8,36025	23,56125	1,50
15.	Clinching	3,85850	10,56100	1,25	7,32600	18,63113	1,25	7,49070	22,19310	1,50	--	--	--	4,63020	12,67320	1,50	5,03400	13,39500	1,50
16.	Flanging	7,64920	12,36520	1,00	21,10950	33,34275	1,25	18,50580	30,78360	1,50	13,07875	21,43375	1,25	9,56150	15,45650	1,25	9,20250	14,51050	1,00
17.	Cohesiveness gluing	6,27055	14,57500	1,25	14,10863	34,99538	1,25	8,88375	21,87300	1,25	7,40313	17,09250	1,25	5,01644	11,66000	1,00	6,96688	14,74563	1,25

Table 8.2.1: Source matrix for the optimal JT Selection Procedure of Industrial Case Study.

State 1	Manufacturing cost for feasible proposal : $M_1(k_1)$																	Optimal solution		
x1 [€]	$k_1 = 1$	$k_1 = 2$	$k_1 = 3$	$k_1 = 4$	$k_1 = 5$	$k_1 = 6$	$k_1 = 7$	$k_1 = 8$	$k_1 = 9$	$k_1 = 10$	$k_1 = 11$	$k_1 = 12$	$k_1 = 13$	$k_1 = 14$	$k_1 = 15$	$k_1 = 16$	$k_1 = 17$	$f_1(x_1)$	Proposal number	Proposal Vector
5											--		13,61	--	10,56	--	--	10,56	15	[15]
10											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
15											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
20											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
25											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
30											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
35											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]
40											11,60		13,61	17,57	10,56	12,36	14,57	10,56	15	[15]

Table 8.2.2: State 1 of the optimal JT Selection Procedure of the Industrial Case Study.

State 2	Manufacturing cost for feasible proposals : {M_2 (k_2) + f_1(x_2-c_2(k_2))}										
x_2 [€]	k_2 = 1	k_2 = 2	k_2 = 3	k_2 = 4	k_2 = 5	k_2= 6	k_2 = 7	k_2 = 8	k_2 = 9	k_2 = 10	k_2 = 11	k_2 = 12
10	18,47+13,61= 32,08 [13] 18,47+10,56=29,03 [15]		--	19,03+13,61=32,64 [13] 19,03+10,56=29,59 [15]	15,63+13,61=29,24 [13] 15,63+10,56=26,19 [15]	--	--	--	--			
15	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+14,57=50,85 [17]	--	--	18,55+13,61=32,16 [13] 18,55+10,56=29,11 [15]			
20	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	--	--	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
25	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
30	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
35	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			
40	18,47+11,60=30,07 [11] 18,47+13,61= 32,08 [13] 18,47+17,57=36,04 [14] 18,47+10,56=29,03 [15] 18,47+12,36=30,83 [16] 18,47+14,57=33,04 [17]		20,88+11,60=32,48 [11] 20,88+13,61=34,49 [13] 20,88+17,57=38,45 [14] 20,88+10,56=31,44 [15] 20,88+12,36=33,24 [16] 20,88+14,57=35,45 [17]	19,03+11,60=30,63 [11] 19,03+13,61=32,64 [13] 19,03+17,57=36,6 [14] 19,03+10,56=29,59 [15] 19,03+12,36=31,39 [16] 19,03+14,57=33,6 [17]	15,63+11,60=27,23 [11] 15,63+13,61=29,24 [13] 15,63+17,57=33,2 [14] 15,63+10,56=26,19 [15] 15,63+12,36=27,99[16] 15,63+14,57=30,20[17]	36,28+11,6=47,88 [11] 36,28+13,61=49,89 [13] 36,28+17,57=53,85 [14] 36,28+10,56=46,84 [15] 36,28+12,36=48,64 [16] 36,28+14,57=50,85 [17]	27,55+11,6=39,15 [11] 27,55+13,61=41,16 [13] 27,55+17,57=45,12 [14] 27,55+10,56=38,11 [15] 27,55+12,36=39,91 [16] 27,55+14,57=42,12 [17]	44,48+11,60=56,08 [11] 44,48+13,61=58,09 [13] 44,48+17,57=62,05 [14] 44,48+10,56=55,04 [15] 44,48+12,36=56,84 [16] 44,48+14,57=59,05 [17]	18,55+11,60=30,15 [11] 18,55+13,61=32,16 [13] 18,55+17,57=36,12 [14] 18,55+10,56=29,11 [15] 18,55+12,36=30,91 [16] 18,55+14,57=33,12 [17]			

Table 8.2.3: First part of Table state 2 of the optimal JT Selection Procedure of the Industrial Case Study.

{$M_2(k_2) + f_1(x_2-c_2(k_2))$}								Optimal solution		
k_2 = 10	k_2 = 11	k_2 = 12	k_2 = 13	k_2 = 14	k_2 = 15	k_2 = 16	k_2 = 17	$f_2(x_2)$	Proposal number	Proposal vector
			--	--	--	--	--	**26,19**	5	[15,5]
			37,25+13,61=50,86 [13] 37,25+10,56=47,81 [15]	--	18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	--	--	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	--	34,99+13,61=48,6 [13] 34,99+10,56=45,55 [15]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+13,61=46,95 [13] 33,34+10,56=43,9 [15]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]
			37,25+11,60=48,85 [11] 37,25+13,61=50,86 [13] 37,25+17,57=54,82 [14] 37,25+10,56=47,81 [15] 37,25+12,36=49,61 [16] 37,25+14,57=51,82 [17]	35,72+11,60=47,32 [11] 35,72+13,61=49,33 [13] 35,72+17,57=53,29 [14] 35,72+10,56=46,28 [15] 35,72+12,36=48,08 [16] 35,72+14,57=50,29 [17]	18,63+11,60=30,23 [11] 18,63+13,61=32,24 [13] 18,63+17,57=36,2 [14] 18,63+10,56=29,19 [15] 18,63+12,36=30,99 [16] 18,63+14,57=33,2 [17]	33,34+11,60=44,94 [11] 33,34+13,61=46,95 [13] 33,34+17,57=50,91 [14] 33,34+10,56=43,9 [15] 33,34+12,36=45,7 [16] 33,34+14,57=47,91 [17]	34,99+11,60=46,59 [11] 34,99+13,61=48,60 [13] 34,99+17,57=52,56 [14] 34,99+10,56=45,55 [15] 34,99+12,36=47,35 [16] 34,99+14,57=49,56 [17]	**26,19**	5	[15,5]

Table 8.2.3: Second part of state 2 of the optimal JT Selection Procedure of the Industrial Case Study.

State 3	Manufacturing cost for feasible proposals : {M_3 (k_3) + $f_2(x_3-c_3(k_3))$}																Optimal solution		
x_3 [€]	$k_3 = 1$	$k_3 = 2$	$k_3 = 3$	$k_3 = 4$	$k_3 = 5$	$k_3 = 6$	$k_3 = 7$	$k_3 = 8$	$k_3 = 9$	$k_3 = 10$	$k_3 = 11$	$k_3 = 12$	$k_3 = 13$	$k_3 = 14$	$k_3 = 15$	$k_3 = 16$	$k_3 = 17$	$f_3(x_3)$	Proposal number	Proposal vector
20											--		35,37+26,19=61,56 [15,5]	--	22,19+26,19=48,38 [15,5]	--	21,87+26,19=48,06 [15,5]	**48,06**	17	[15,5,17]
25											--		35,37+26,19=61,56 [15,5]	31,43+26,19=57,62 [15,5]	22,19+26,19=48,38 [15,5]	--	21,87+26,19=48,06 [15,5]	**48,06**	17	[15,5,17]
30											22,50+26,19=48,69 [15,5]		35,37+26,19=61,56 [15,5]	31,43+26,19=57,62 [15,5]	22,19+26,19=48,38 [15,5]	30,78+26,19=56,97 [15,5]	21,87+26,19=48,06 [15,5]	**48,06**	17	[15,5,17]
35											22,50+26,19=48,69 [15,5]		35,37+26,19=61,56 [15,5]	31,43+26,19=57,62 [15,5]	22,19+26,19=48,38 [15,5]	30,78+26,19=56,97 [15,5]	21,87+26,19=48,06 [15,5]	**48,06**	17	[15,5,17]
40											22,50+26,19=48,69 [15,5]		35,37+26,19=61,56 [15,5]	31,43+26,19=57,62 [15,5]	22,19+26,19=48,38 [15,5]	30,78+26,19=56,97 [15,5]	21,87+26,19=48,06 [15,5]	**48,06**	17	[15,5,17]

Table 8.2.4: State 3 of the optimal JT Selection Procedure of Industrial Case Study.

State 4	Manufacturing cost for feasible proposals : $\{M_4(k_4) + f_3(x_4 - c_4(k_4))\}$										
x_4 [€]	$k_4 = 1$	$k_4 = 2$	$k_4 = 3$	$k_4 = 4$	$k_4 = 5$	$k_4 = 6$	$k_4 = 7$	$k_4 = 8$	$k_4 = 9$	$k_4 = 10$	$k_4 = 11$
25	--	--	9,85+48,06=57,91 [15,5,17]	11,68+48,06=59,74 [15,5,17]	10,41+48,06=58,47 [15,5,17]		--	--	--	--	
30	12,09+48,06=60,15 [15,5,17]	--	9,85+48,06=57,91 [15,5,17]	11,68+48,06=59,74 [15,5,17]	10,41+48,06=58,47 [15,5,17]		15,97+48,06=64,03 [15,5,17]	21,08+48,06=69,14 [15,5,17]	14,18+48,06=62,24 [15,5,17]	10,11+48,06=58,17 [15,5,17]	
35	12,09+48,06=60,15 [15,5,17]	--	9,85+48,06=57,91 [15,5,17]	11,68+48,06=59,74 [15,5,17]	10,41+48,06=58,47 [15,5,17]		15,97+48,06=64,03 [15,5,17]	21,08+48,06=69,14 [15,5,17]	14,18+48,06=62,24 [15,5,17]	10,11+48,06=58,17 [15,5,17]	
40	12,09+48,06=60,15 [15,5,17]	--	9,85+48,06=57,91 [15,5,17]	11,68+48,06=59,74 [15,5,17]	10,41+48,06=58,47 [15,5,17]		15,97+48,06=64,03 [15,5,17]	21,08+48,06=69,14 [15,5,17]	14,18+48,06=62,24 [15,5,17]	10,11+48,06=58,17 [15,5,17]	

x_4 [€]	$k_4 = 12$	$k_4 = 13$	$k_4 = 14$	$k_4 = 15$	$k_4 = 16$	$k_4 = 17$	Optimal solution		
							$f_4(x_4)$	Proposal number	Proposal vector
25			--		--	--	**57,91**	3	[15,5,17,3]
30			18,44+48,06=66,5 [15,5,17]		--	17,09+48,06=65,15 [15,5,17]	**57,91**	3	[15,5,17,3]
35			18,44+48,06=66,5 [15,5,17]		21,43+48,06=69,49 [15,5,17]	17,09+48,06=65,15 [15,5,17]	**57,91**	3	[15,5,17,3]
40			18,44+48,06=66,5 [15,5,17]		21,43+48,06=69,49 [15,5,17]	17,09+48,06=65,15 [15,5,17]	**57,91**	3	[15,5,17,3]

Table 8.2.5: State 4 of the optimal JT Selection Procedure of Industrial Case Study.

State 5	Manufacturing cost for feasible proposals :											
x_5 [€]	$k_5 = 1$	$k_5 = 2$	$k_5 = 3$	$k_5 = 4$	$k_5 = 5$	$k_5 = 6$	$k_5 = 7$	$k_5 = 8$	$k_5 = 9$	$k_5 = 10$	$k_5 = 11$	$k_5 = 12$	$k_5 = 13$
30											--		17,02+57,91=74,93 [15,5,17,3]
35											11,60+57,91=69,51 [15,5,17,3]		17,02+57,91=74,93 [15,5,17,3]
40											11,60+57,91=69,51 [15,5,17,3]		17,02+57,91=74,93 [15,5,17,3]

$\{M_5(k_5) + f_4(x_5 - c_5(k_5))\}$				Optimal solution		
$k_5 = 14$	$k_5 = 15$	$k_5 = 16$	$k_5 = 17$	$f_5(x_5)$	Proposal number	Proposal vector
--	12,67+57,91=70,58 [15,5,17,3]	--	--	**70,58**	15	[15,5,17,3,15]
17,57+57,91=75,48 [15,5,17,3]	12,67+57,91=70,58 [15,5,17,3]	15,45+57,91=73,36 [15,5,17,3]	11,66+57,91=69,57 [15,5,17,3]	**69,51**	11	[15,5,17,3,11]
17,57+57,91=75,48 [15,5,17,3]	12,67+57,91=70,58 [15,5,17,3]	15,45+57,91=73,36 [15,5,17,3]	11,66+57,91=69,57 [15,5,17,3]	**69,51**	11	[15,5,17,3,11]

Table 8.2.6: State 5 of the optimal JT Selection Procedure of Industrial Case Study.

State 6	Manufacturing cost for feasible proposals : $\{M_6(k_6) + f_5(x_6 - c_6(k_6))\}$									
x_6 [€]	$k_6 = 1$	$k_6 = 2$	$k_6 = 3$	$k_6 = 4$	$k_6 = 5$	$k_6 = 6$	$k_6 = 7$	$k_6 = 8$	$k_6 = 9$	$k_6 = 10$	$k_6 = 11$
35	7,10+70,58=77,68 [15,5,17,3,15]	--	10,29+70,58=80,87[15,5,17,3,15]	9,75+70,58=80,33 [15,5,17,3,15]	9,82+70,58=80,4 [15,5,17,3,15]	19,22+70,58=89,8 [15,5,17,3,15]	--	--	8,37+70,58=78,95 [15,5,17,3,15]	7,50+70,58=78,08 [15,5,17,3,15]	--
40	7,10+69,51=76,61 [15,5,17,3,11]	--	10,29+69,51=79,8 [15,5,17,3,11]	9,75+69,51=79,26 [15,5,17,3,11]	9,82+69,51=79,33 [15,5,17,3,11]	19,22+69,51=88,73 [15,5,17,3,11]	14,475+69,51=83,98 [15,5,17,3,11]	19,71+69,51=89,22 [15,5,17,3,11]	8,37+69,51=77,88 [15,5,17,3,11]	7,50+69,51=77,01 [15,5,17,3,11]	--

							Optimal solution		
x_6 [€]	$k_6 = 12$	$k_6 = 13$	$k_6 = 14$	$k_6 = 15$	$k_6 = 16$	$k_6 = 17$	$f_6(x_6)$	Proposal number	Proposal vector
35	11,59+70,58=82,17 [15,5,17,3,15]	--	--	13,39+70,58=83,97 [15,5,17,3,15]	--	--	77,68	1	[15,5,17,3,15,1]
40	11,59+69,51=81,10 [15,5,17,3,11]	23,33+69,51=92,84 [15,5,17,3,11]	23,56+69,51=93,07 [15,5,17,3,11]	13,39+69,51=82,90 [15,5,17,3,11]	14,51+69,51=84,02 [15,5,17,3,11]	14,74+69,51=84,25 [15,5,17,3,11]	76,61	1	[15,5,17,3,11,1]

Table 8.2.7: State 6 of the optimal JT Selection Procedure of Industrial Case Study.

Permissible solution for C ≤ 40		1. Joining Side	2. Joining Side	3. Joining Side	4. Joining Side	5. Joining Side	6. Joining Side	Total cost per wheelhouse
Proposal vector:	[15, 5,17, 3, 11,1]	Clinching	MAG welding	Cohesiveness gluing	MIG welding	Laser brazing	Spot welding	
Manufacturing cost M per JS		0,10561	0,15633	0,21873	0,09856	0,116	0,0710625	0,7661
Investment cost c per JS		0,03859	0,061128	0,0888375	0,03325	0,083	0,0331875	0,3377

JS number	1	2	3	4	5	6	Total number of SWC's
Ascertained JT Combination	Clinching	MAG welding	Cohesiveness gluing	MIG welding	Laser brazing	Spot welding	
JS Material Combination	Aluminium - Steel	Aluminium-Aluminium	Aluminium-High tensile steel	Steel-High tensile steel	Aluminium-Steel	Steel-Steel	
Number of WC	4	9	6	5	4	5	
SWCC	1,72896	1,44856	2,45857	1,581	2,98261	1	
JSC	1,25	1,00	1,25	1,00	1,00	1,25	
Number of SWC's	8,6448	13,03704	18,439275	7,905	11,93044	6,25	66,206555

Table 8.2.6: Solution table and total number SWC's of Industrial Case Study.

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Aluminium - Aluminium			Alu. - High tensile steel			Steel - High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	JT's / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	0,06566	0,18473	1,25	--	--	--	0,05232	0,12098	1,50	--	--	--	**0,03319**	**0,07106**	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	0,43718	0,93158	1,50	--	--	--	0,28669	0,61088	1,25
3.	MIG welding	--	--	--	0,07706	0,20880	1,25	--	--	--	**0,03325**	**0,09856**	1,00	--	--	--	0,03921	0,10298	1,25
4.	Tandem MIG welding	--	--	--	0,05445	0,19032	1,25	--	--	--	0,03448	0,11687	1,25	--	--	--	0,02814	0,09750	1,25
5.	MAG welding	--	--	--	**0,06113**	**0,15633**	1,00	--	--	--	0,03970	0,10415	1,00	--	--	--	0,03654	0,09825	1,00
6.	WIG welding	--	--	--	0,07794	0,36288	1,00	--	--	--	--	--	--	--	--	--	0,04109	0,19220	1,00
7.	Laser-welding (CO_2)	--	--	--	0,17089	0,27551	1,25	--	--	--	0,09300	0,15975	1,25	--	--	--	0,09119	0,14475	1,25
8.	Laser-welding (Diodes)	--	--	--	0,18992	0,44483	1,25	--	--	--	0,09963	0,21081	1,25	--	--	--	0,09519	0,19713	1,25
9.	Laser-welding (YAG)	--	--	--	0,09199	0,18554	1,00	--	--	--	0,06165	0,14185	1,00	--	--	--	0,04053	0,08379	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	0,05087	0,10110	1,50	--	--	--	0,04091	0,07506	1,25
11.	Laser brazing	0,08300	0,11600	1,00	--	--	--	0,15983	0,22508	1,25	--	--	--	**0,08300**	**0,11600**	1,00	0,12794	0,17700	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0,03230	0,11590	1,00
13.	Punch riveting	0,03198	0,13616	1,00	0,09129	0,37259	1,25	0,07620	0,35378	1,50	--	--	--	0,03997	0,17020	1,25	0,05907	0,23333	1,50
14.	Blind riveting	0,06006	0,17575	1,25	0,12540	0,35727	1,25	0,10580	0,31440	1,50	0,06245	0,18449	1,00	0,06006	0,17575	1,25	0,08360	0,23561	1,50
15.	Clinching	**0,03859**	**0,10561**	1,25	0,07326	0,18631	1,25	0,07491	0,22193	1,50	--	--	--	0,04630	0,12673	1,50	0,05034	0,13395	1,50
16.	Flanging	0,07649	0,12365	1,00	0,21110	0,33343	1,25	0,18506	0,30784	1,50	0,13079	0,21434	1,25	0,09562	0,15457	1,25	0,09203	0,14511	1,00
17.	Cohesiveness gluing	0,06271	0,14575	1,25	0,14109	0,34995	1,25	**0,08884**	**0,21873**	1,25	0,07403	0,17093	1,25	0,05016	0,11660	1,00	0,06967	0,14746	1,25

Table 8.2.7: Source Matrix with marked JT Solution Vector for optimal JT Selection procedure.

9. Presentation of the Research Methodology

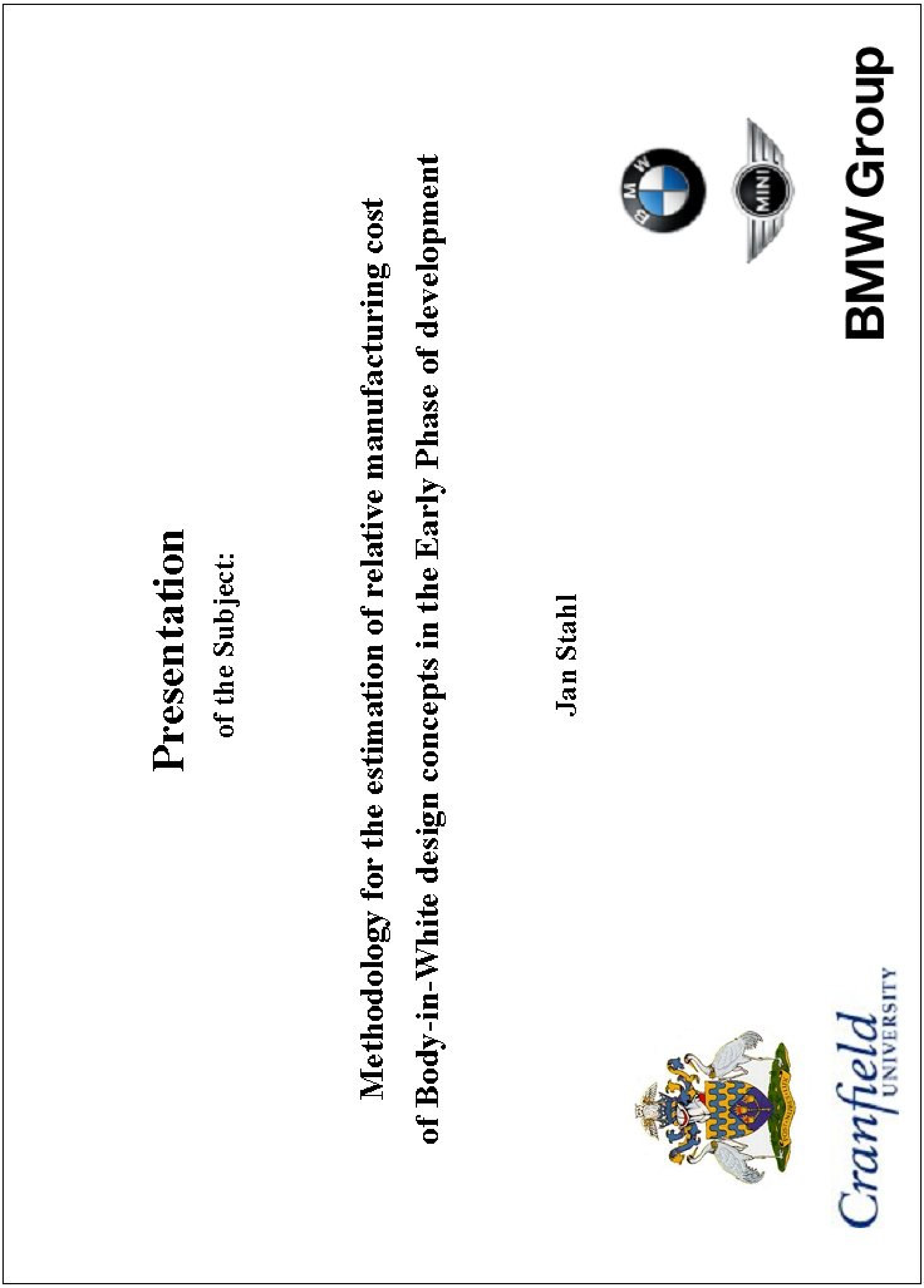


Figure 9.1: Title page of the Presentation of the Research Methodology.

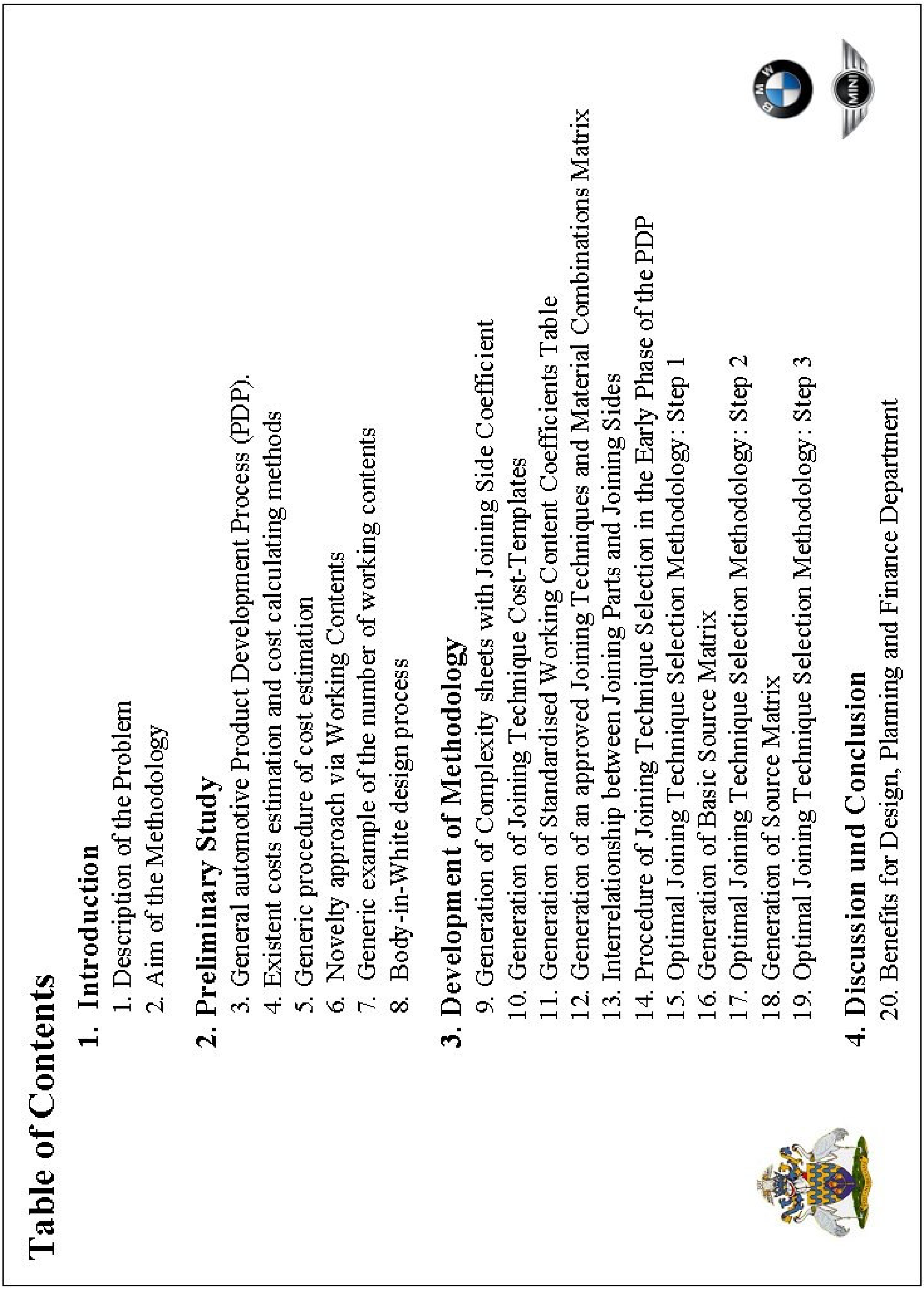


Figure 9.2: Table of Contents page of the Presentation of the Research Methodology.

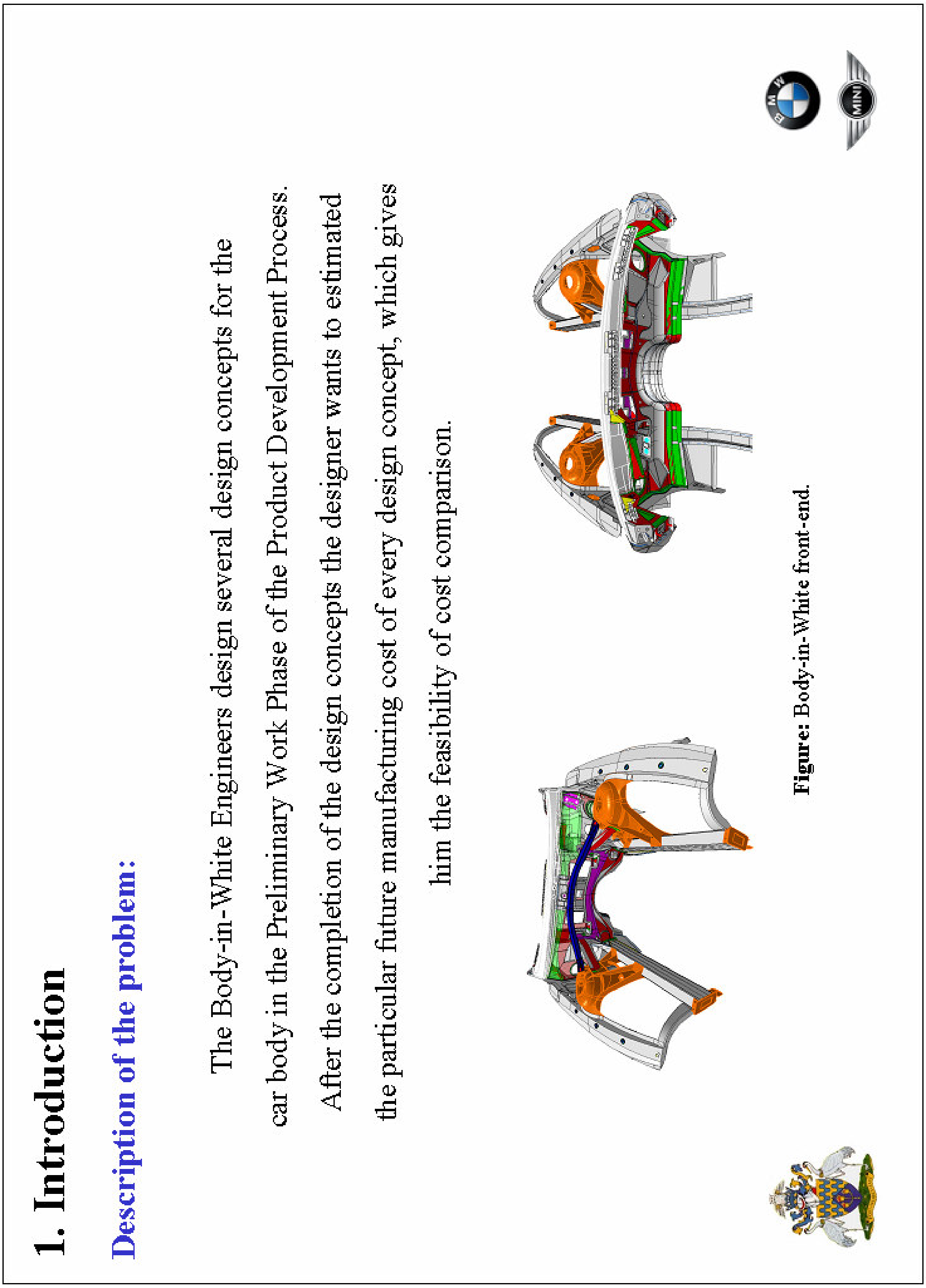


Figure 9.3: Page 3 of the Presentation of the Research Methodology.

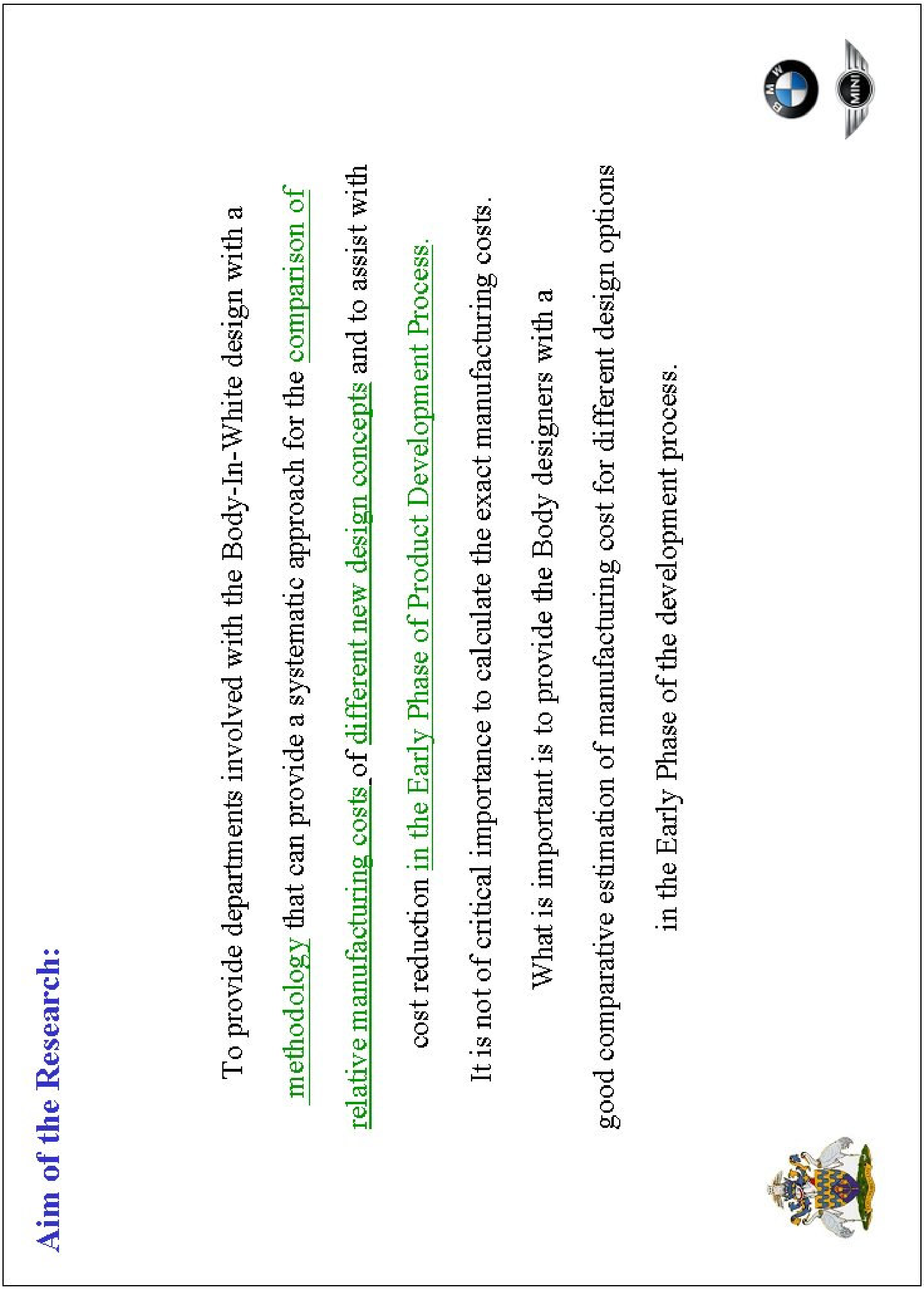


Figure 9.4: Page 4 of the Presentation of the Research Methodology.

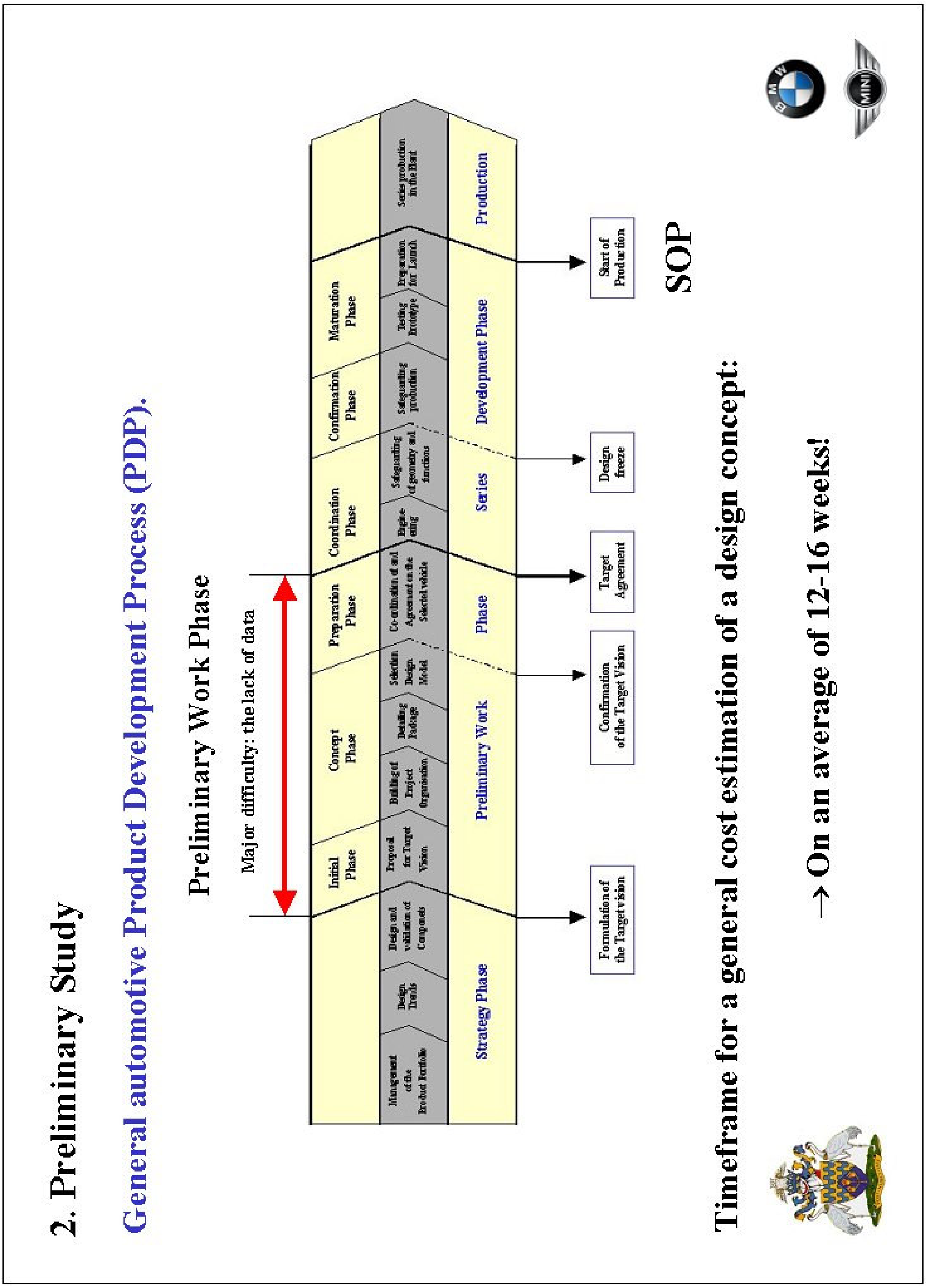


Figure 9.5: Page 5 of the Presentation of the Research Methodology.

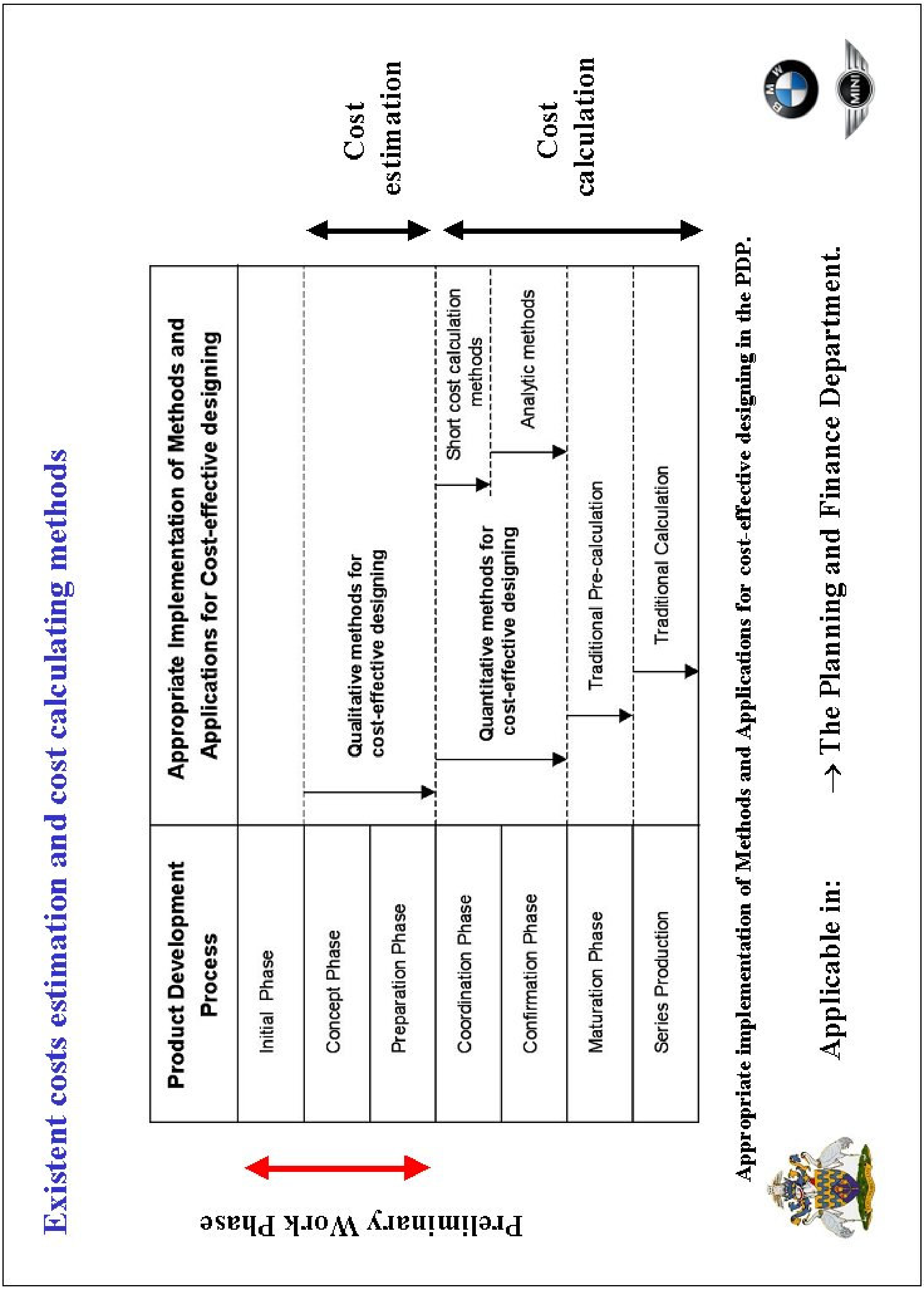


Figure 9.6: Page 6 of the Presentation of the Research Methodology.

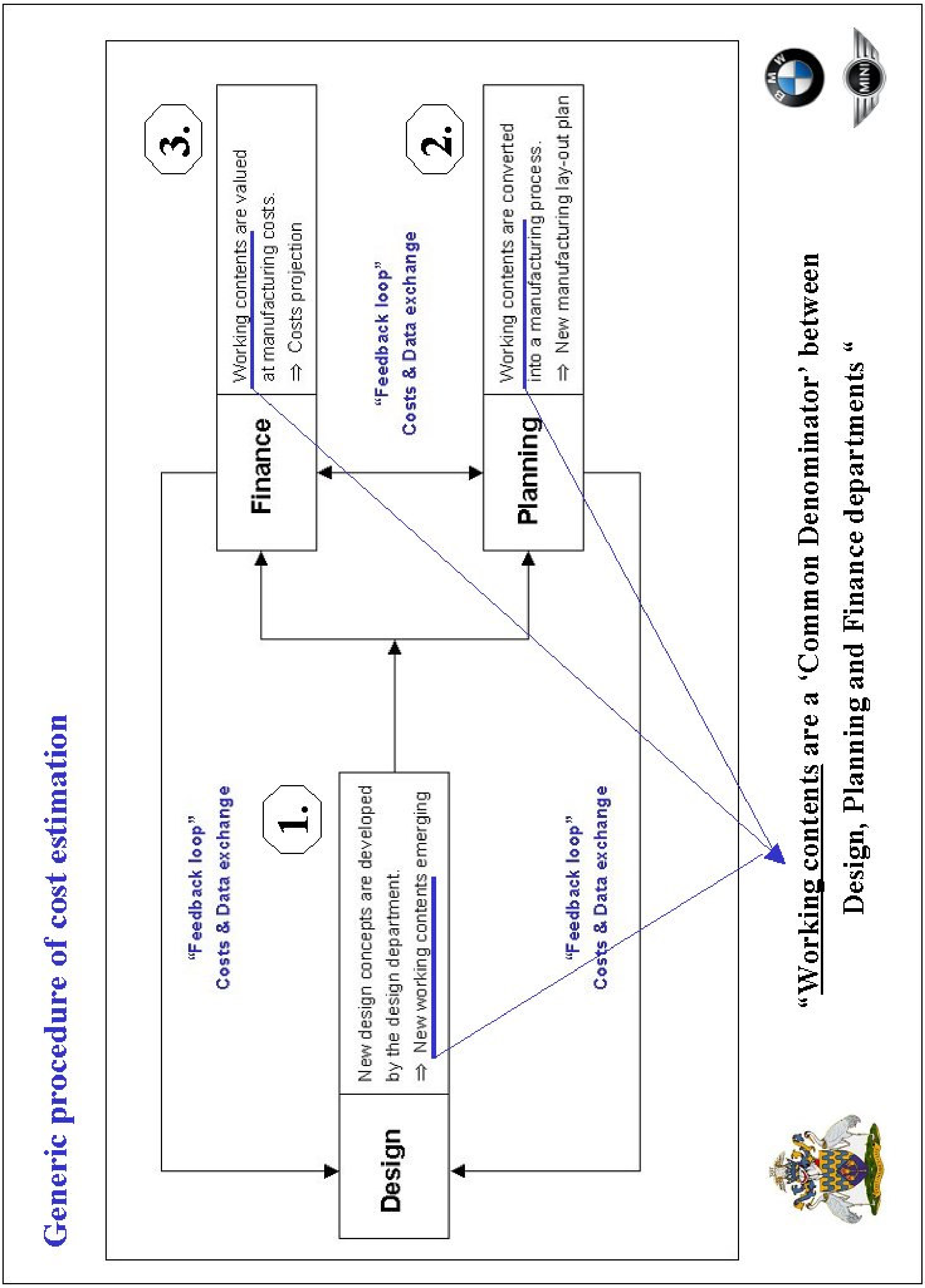


Figure 9.7: Page 7 of the Presentation of the Research Methodology.

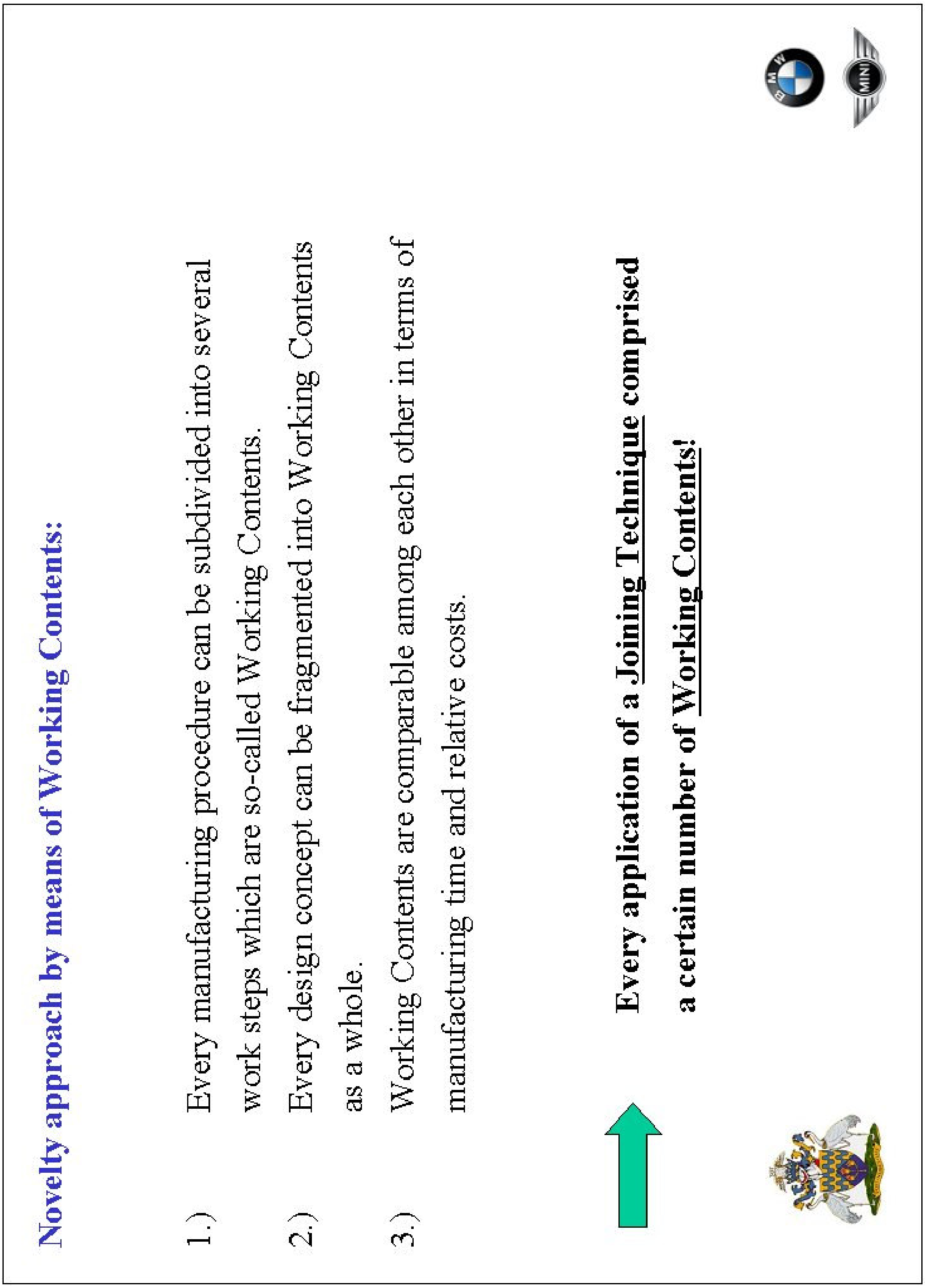


Figure 9.8: Page 8 of the Presentation of the Research Methodology.

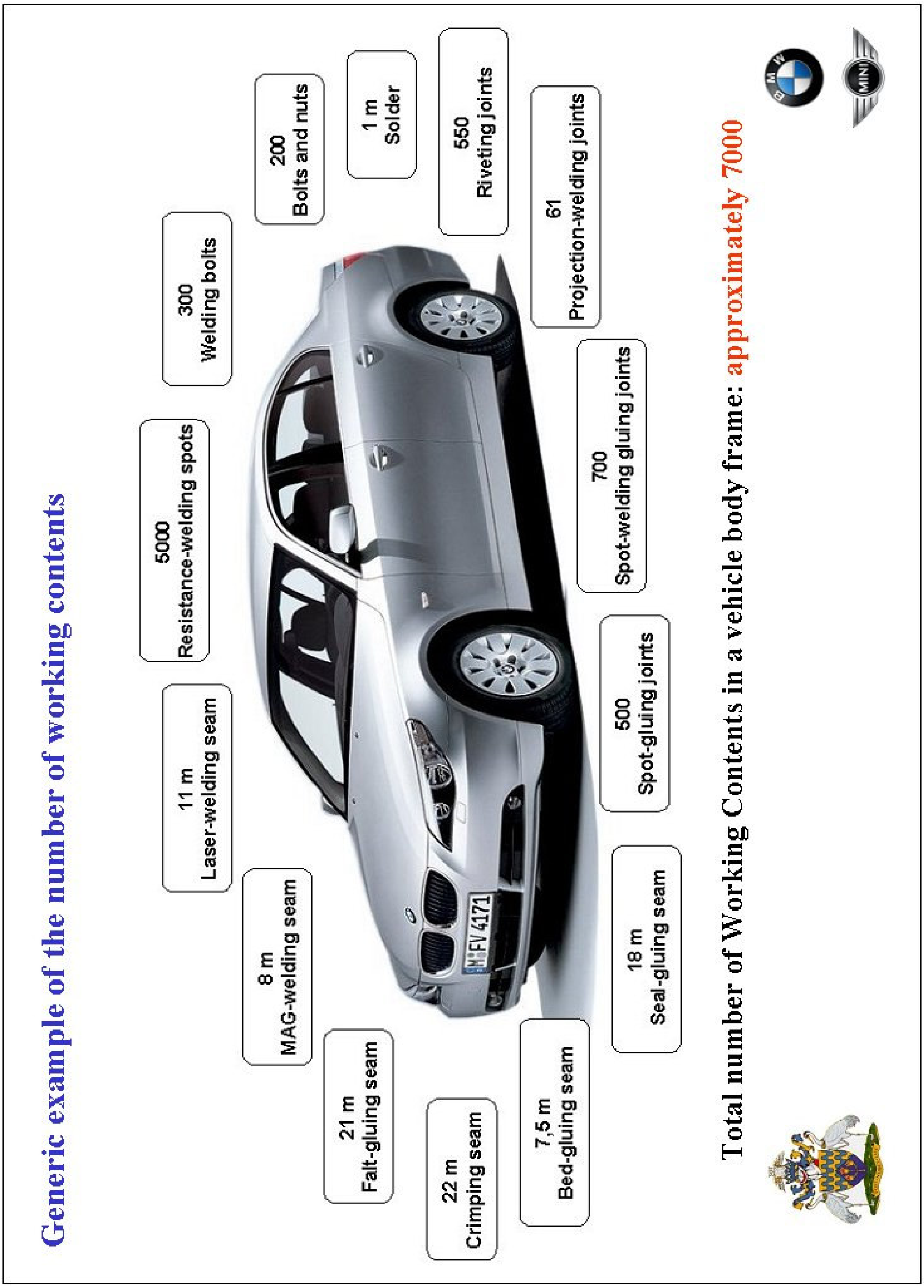


Figure 9.9: Page 9 of the Presentation of the Research Methodology.

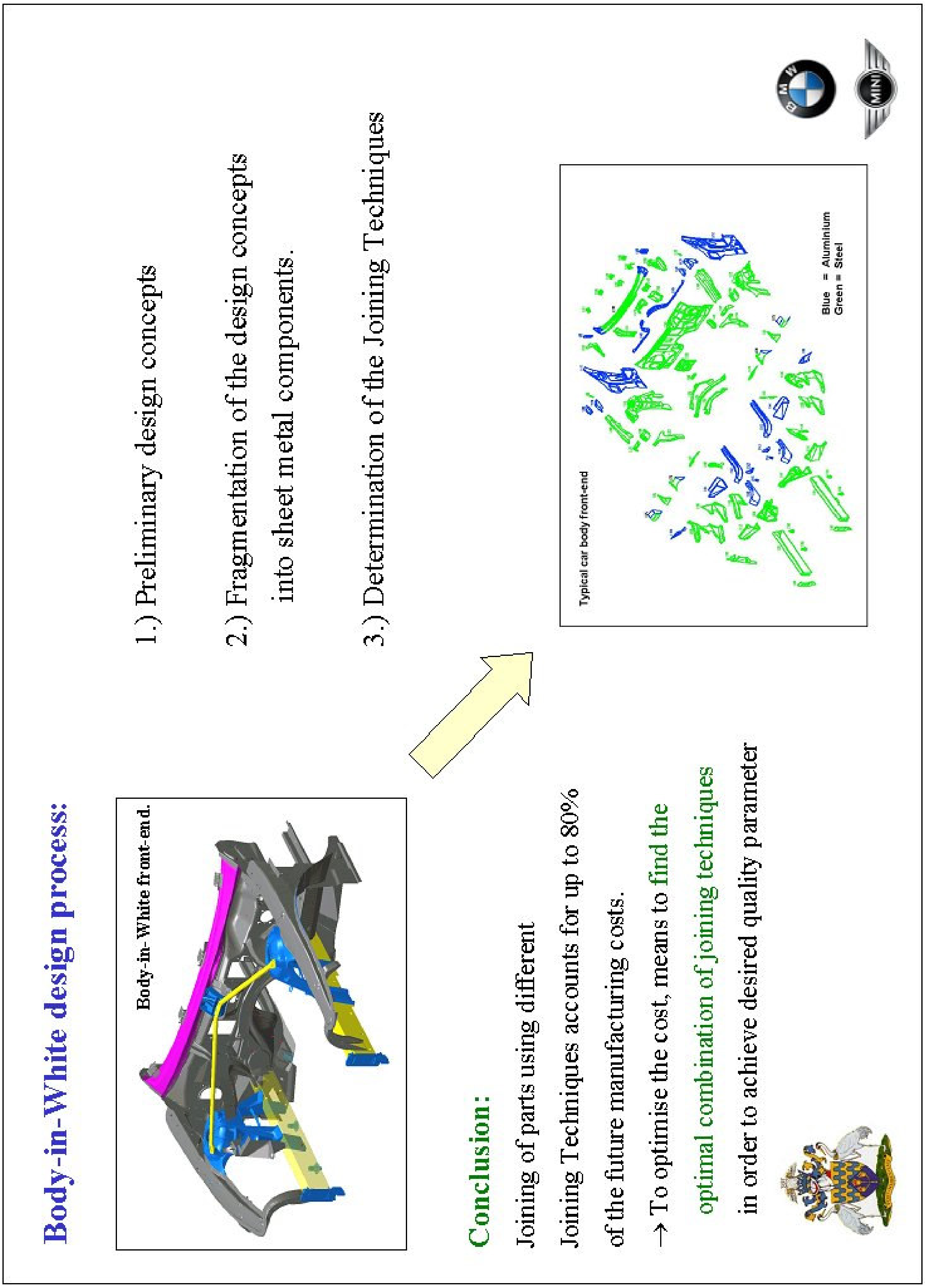


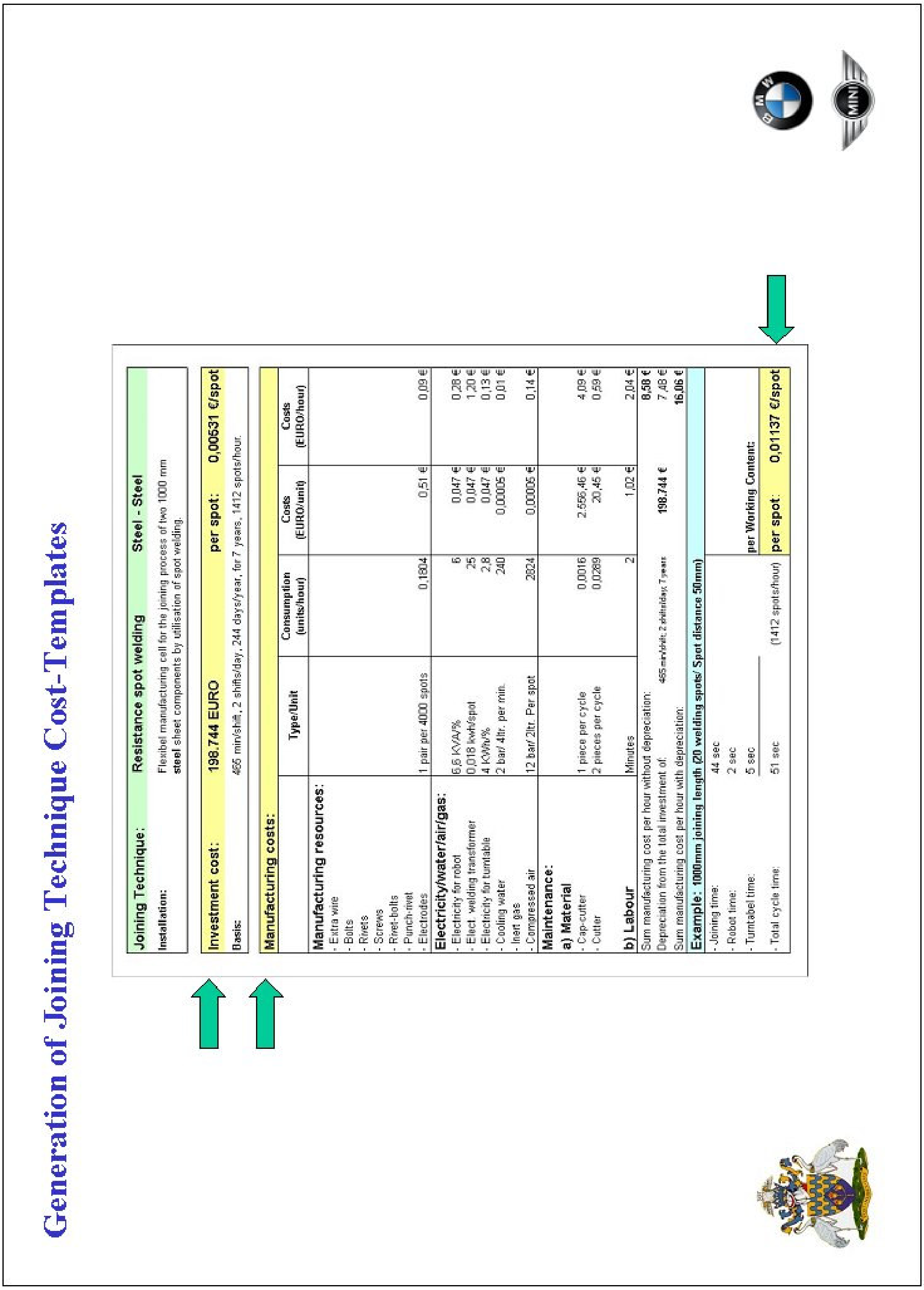
Figure 9.10: Page 10 of the Presentation of the Research Methodology.

3. Development of Methodology

Generation of Complexity sheets with Joining Side Coefficient

Spot welding			
Complexity level 1 JS Coefficient = 1,00 100% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Variation of blank sheet thickness 0%, two-blank sheet-welding of equal blank sheet thickness, blank sheet thickness > 1,5mm. Effective joining width according to DIN: 20mm < effective width of the joining blank sheet. Blank sheet surface without discoloration, free of oil, free of grease, without coating, not galvanised. Great degree of freedom for the welding gun, little steel in "secondary welding gun window", easily positioning of the welding gun because of an appropriate blank sheet contour => plane part contour.	Plane part contour 100% cycle time
Complexity level 2 JS Coefficient = 1,25 125% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Two-blank sheet-welding of different blank sheet thickness 0,7mm < blank sheet thickness < 1,5mm, variation of blank sheet thickness < 20%. Effective joining width outside of DIN reference, effective joining width narrow, 20mm > effective width of the joining blank sheet. Blank sheet surface without discoloration, without coating. Average volume of steel in the "secondary welding gun window", normal size of the welding gun (length of piole X < 800m), normal positioning of welding gun because of an appropriate blank sheet contour => curved part contour.	Curved part contour 125% cycle time
Complexity level 3 JS Coefficient = 1,50 150% cycle time	**1. Blank sheet thickness:** **2. Effective width:** **3. Surface condition:** **4. Accessibility:**	Two or three-blank sheet-welding of equal blank sheet thickness 0,7mm < blank sheet thickness < 1,5mm, variation of blank sheet thickness > 20%. Joining width under limit, 15mm > effective width of the joining blank sheet. Blank sheet surface with discoloration, heavily oiled, greased, galvanised. Shortage of space, great amount of steel in "secondary welding gun window", big welding gun (length of piole X > 800mm), difficult positioning of welding gun because of a complicate blank sheet contour => stepped part contour.	Stepped part contour 150% cycle time

Figure 9.11: Page 11 of the Presentation of the Research Methodology.



Joining Technique:	**Resistance spot welding**	**Steel - Steel**		
Installation:	Flexibel manufacturing cell for the joining process of two 1000 mm **steel** sheet components by utilisation of spot welding.			
Investment cost:	**198.744 EURO**	**per spot:**	**0,00531 €/spot**	
Basis:	465 min/shift, 2 shifts/day, 244 days/year, for 7 years, 1412 spots/hour.			
Manufacturing costs:				
	Type/Unit	**Consumption (units/hour)**	**Costs (EURO/unit)**	**Costs (EURO/hour)**
Manufacturing resources:				
- Extra wire				
- Bolts				
- Rivets				
- Screws				
- Rivet-bolts				
- Punch-rivet				
- Electrodes	1 pair per 4000 spots	0,1804	0,51 €	0,09 €
Electricity/water/air/gas:				
- Electricity for robot	6,6 KVA/%	6	0,047 €	0,28 €
- Elect. welding transformer	0,018 kwh/spot	25	0,047 €	1,20 €
- Electricity for turntable	4 KWh/%	2,8	0,047 €	0,13 €
- Cooling water	2 bar/ 4ltr. per min.	240	0,00005 €	0,01 €
- Inert gas				
- Compressed air	12 bar/ 2ltr. Per spot	2824	0,00005 €	0,14 €
Maintenance:				
a) Material				
- Cap-cutter	1 piece per cycle	0,0016	2.556,46 €	4,09 €
- Cutter	2 pieces per cycle	0,0289	20,45 €	0,59 €
b) Labour	Minutes	2	1,02 €	2,04 €
Sum manufacturing cost per hour without depreciation:				**8,58 €**
Depreciation from the total investment of:		465 min/shift; 2 shifts/day; 7 years	**198.744 €**	7,48 €
Sum manufacturing cost per hour with depreciation:				**16,06 €**
Example: 1000mm joining length (20 welding spots/ Spot distance 50mm)				
- Joining time:	44 sec			
- Robot time:	2 sec			
- Turntabel time:	5 sec		**per Working Content:**	
- Total cycle time:	51 sec	(1412 spots/hour)	**per spot:**	**0,01137 €/spot**

Figure 9.12: Page 12 of the Presentation of the Research Methodology.

Generation of Standardised Working Content Coefficients Table

Joining side Material:		Steel - Steel	Steel - High tensile Steel	Steel - Aluminium	Aluminium - Aluminium	Aluminium - High tensile steel
No.	Joining Tech. / SWCC	$SWCC_{st-st}$	$SWCC_{st-htst}$	$SWCC_{st-alu}$	$SWCC_{alu-alu}$	$SWCC_{alu-htst}$
1.	Spot welding	1,00000	1,38525	--	1,33429	--
2.	Spot weld-gluing	8,60971	10,94125	--	--	--
3.	MIG welding	1,36391	1,58100	--	1,52338	--
4.	Tandem MIG welding	1,20516	1,45174	--	1,30438	--
5.	MAG welding	1,61613	1,72482	--	1,44856	--
6.	WIG welding	2,79724	--	--	2,93645	--
7.	Laser-welding (CO_2)	2,26319	2,42446	--	2,37890	--
8.	Laser-welding (Diodes)	2,80396	2,97776	--	3,38261	--
9.	Laser-welding (YAG)	1,49053	2,44005	--	1,84874	--
10.	Projection welding	1,11241	1,21475	--	--	--
11.	Laser brazing	2,92506	--	2,98261	--	3,07674
12.	MAG brazing	1,77698	--	--	--	--
13.	Punch riveting	2,33729	--	2,52002	2,47206	2,86427
14.	Blind riveting	2,55168	2,96085	2,82740	2,57218	2,79910
15.	Clinching	1,47314	--	1,72896	1,38327	1,97734
16.	Flanging	2,84329	3,31055	2,99976	2,90180	3,28333
17.	Cohesiveness gluing	2,08273	2,34970	2,49947	2,61679	2,45857

Figure 9.13: Page 13 of the Presentation of the Research Methodology.

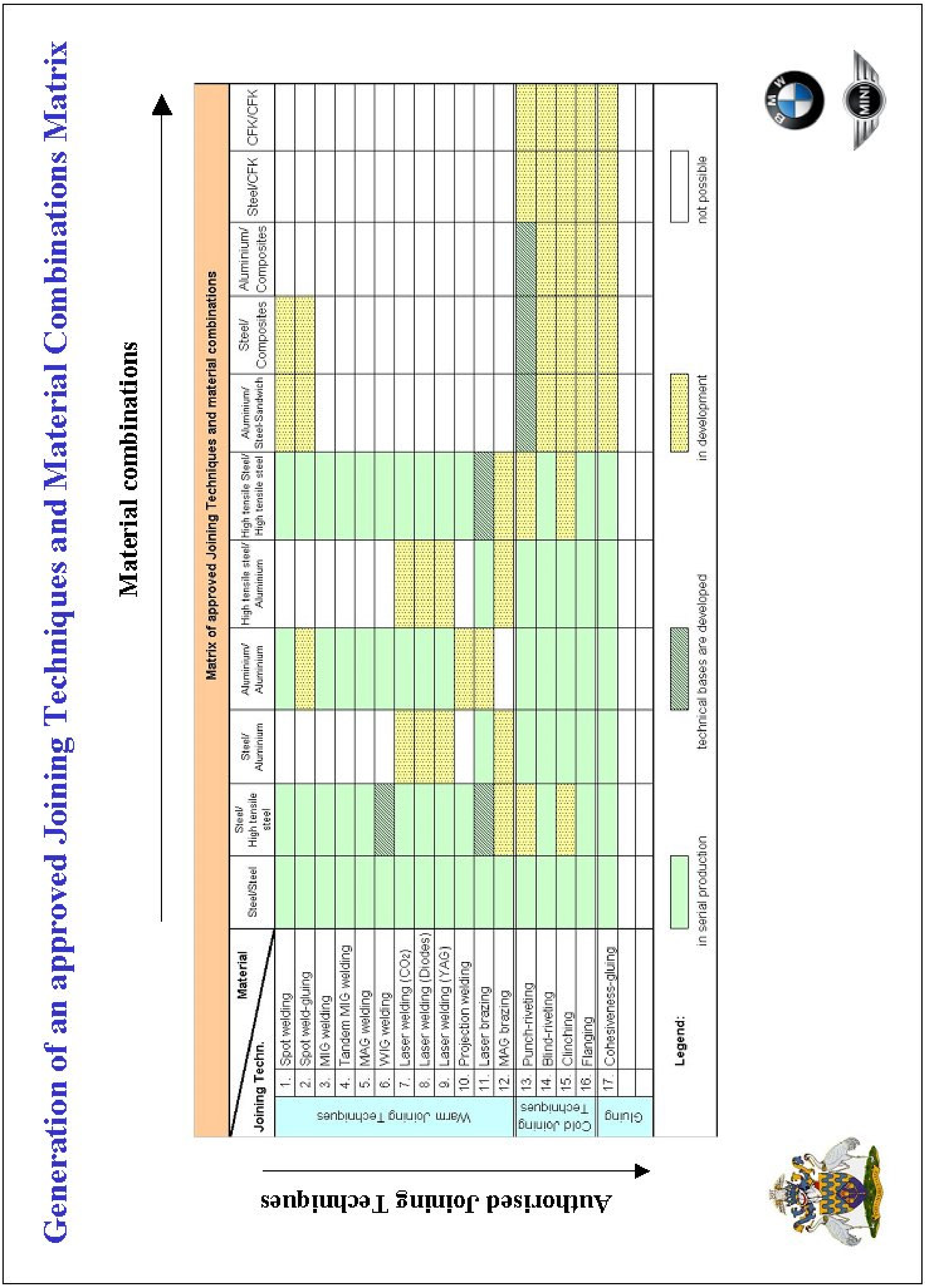


Figure 9.14: Page 14 of the Presentation of the Research Methodology.

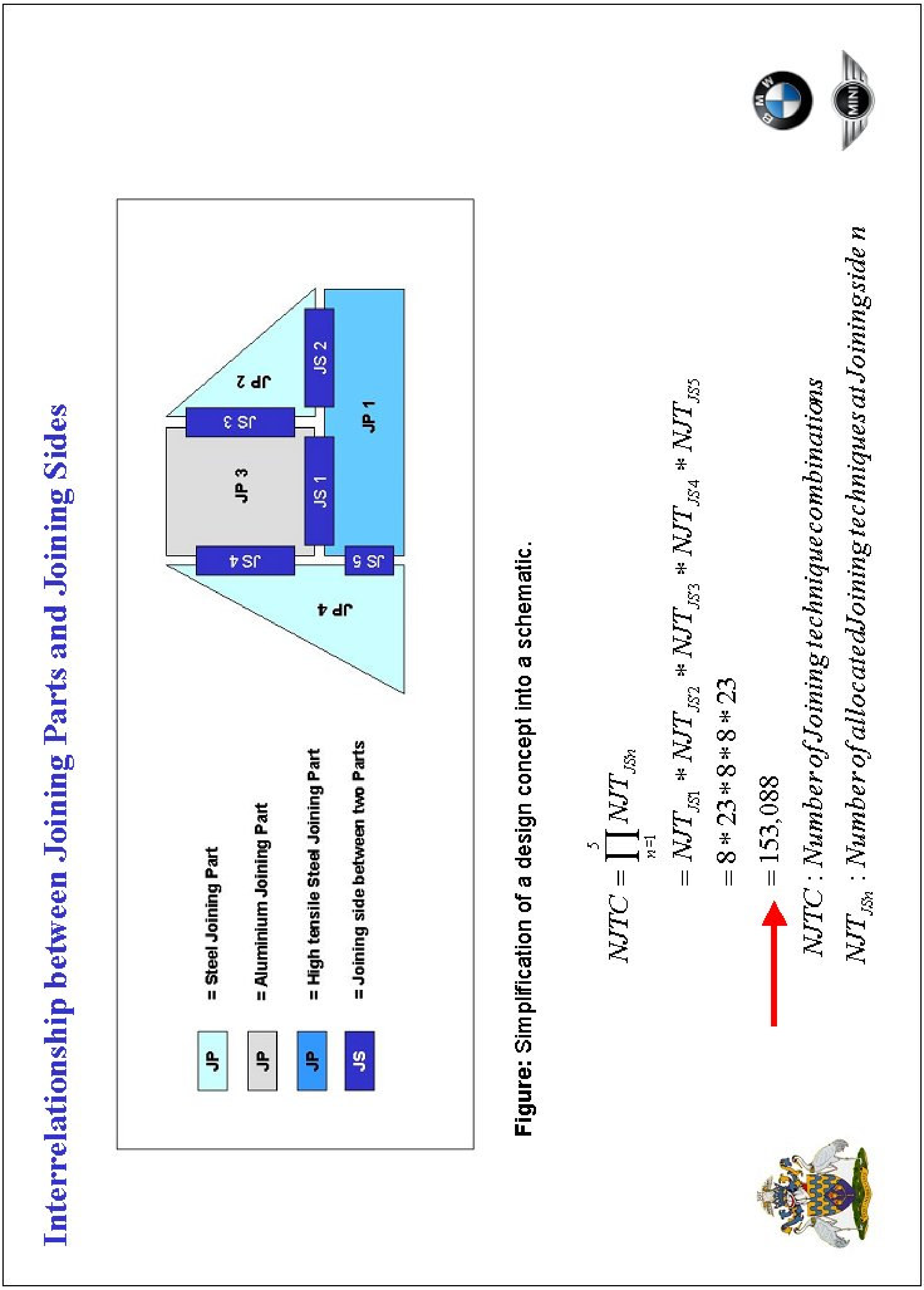


Figure 9.15: Page 15 of the Presentation of the Research Methodology.

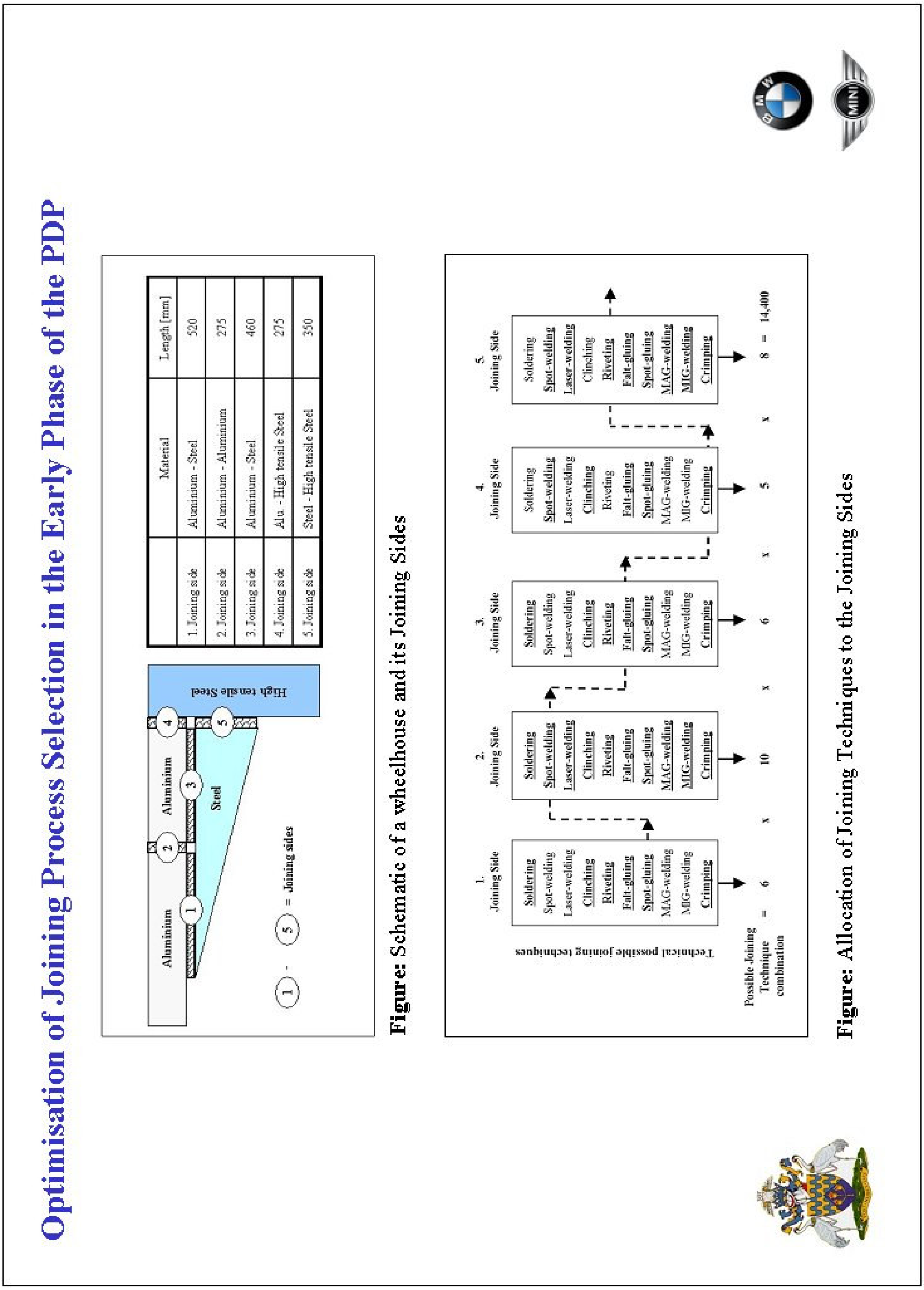


Figure 9.16: Page 16 of the Presentation of the Research Methodology.

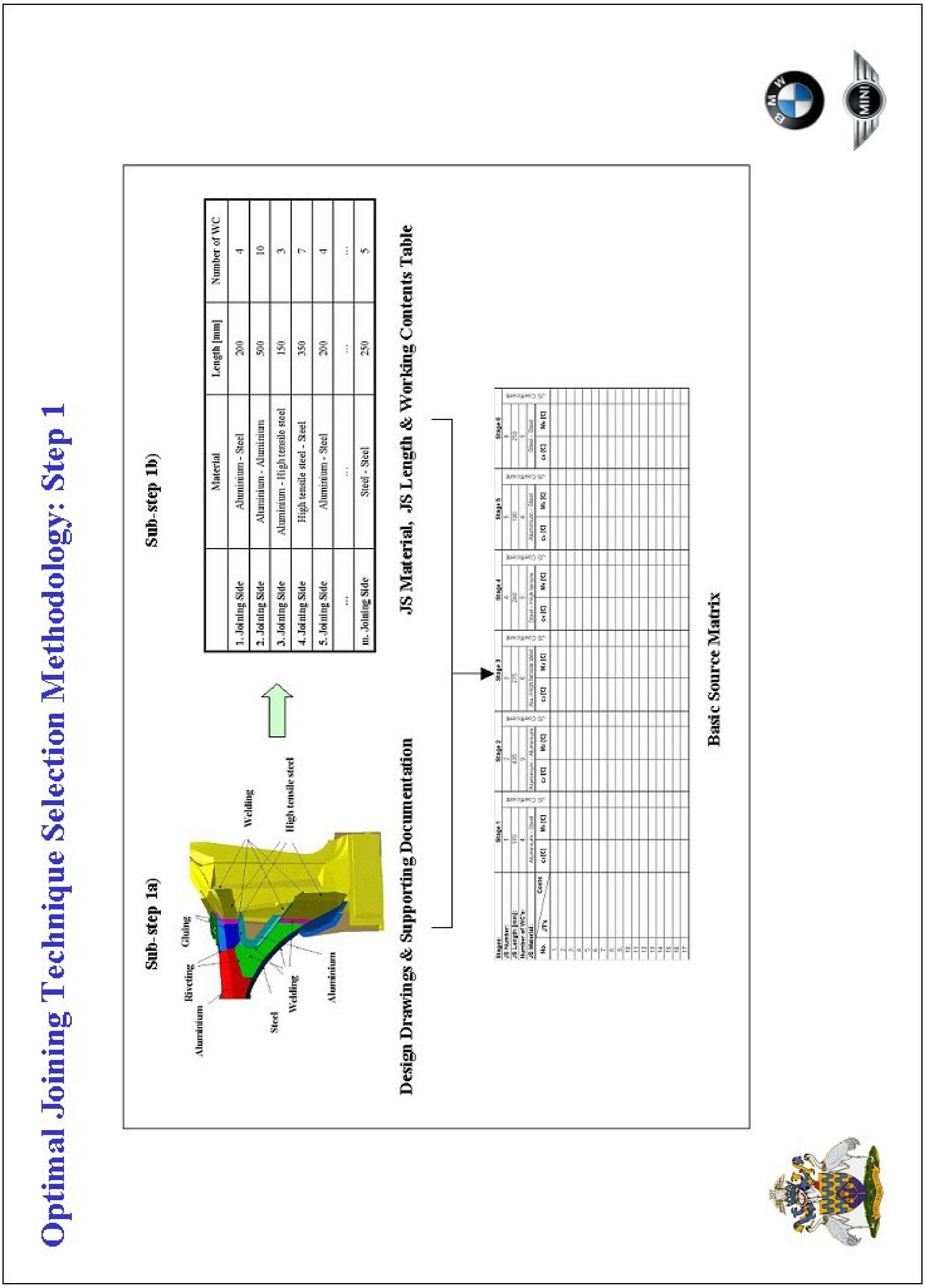


Figure 9.17: Page 17 of the Presentation of the Research Methodology.

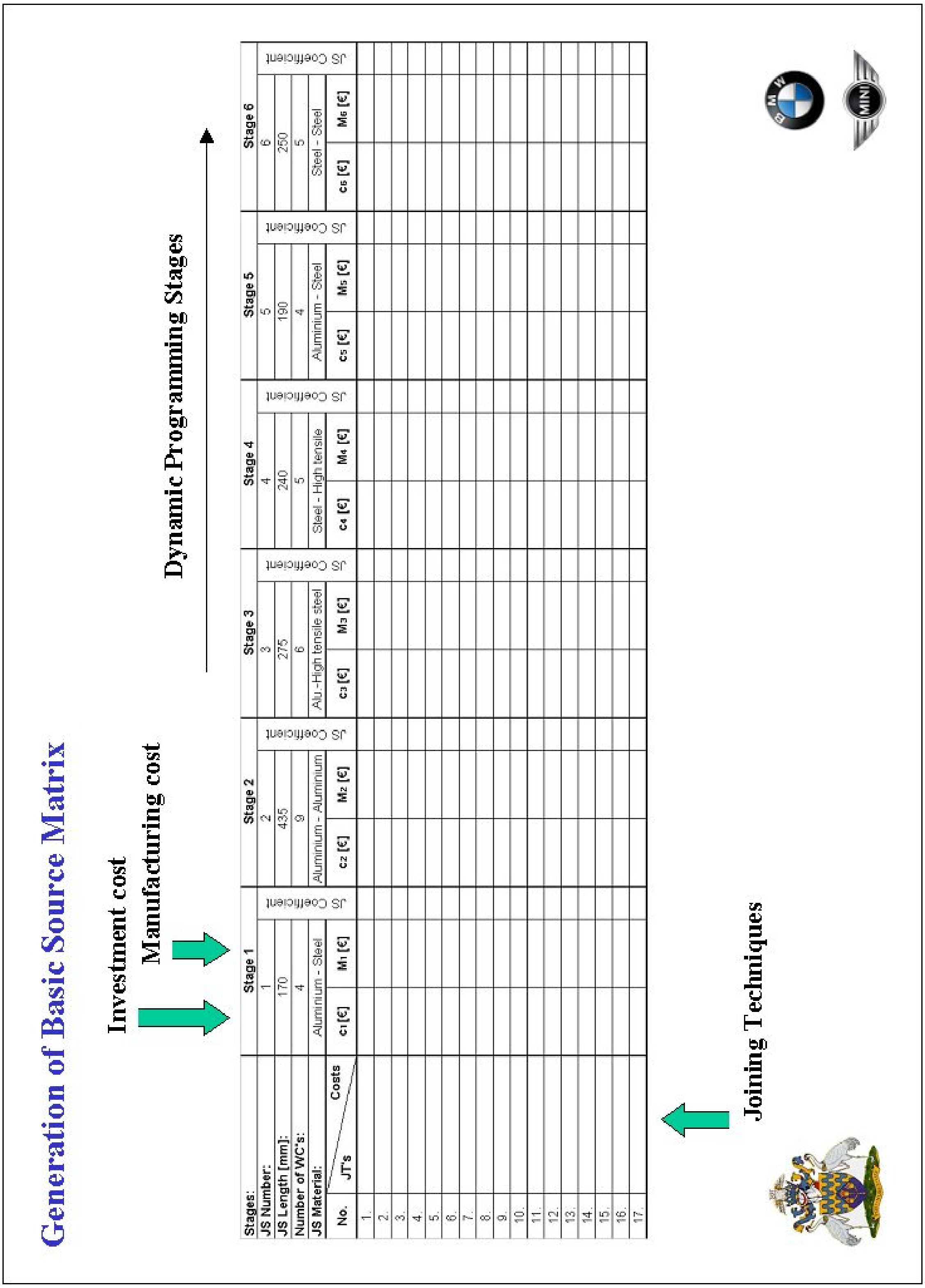


Figure 9.18: Page 18 of the Presentation of the Research Methodology.

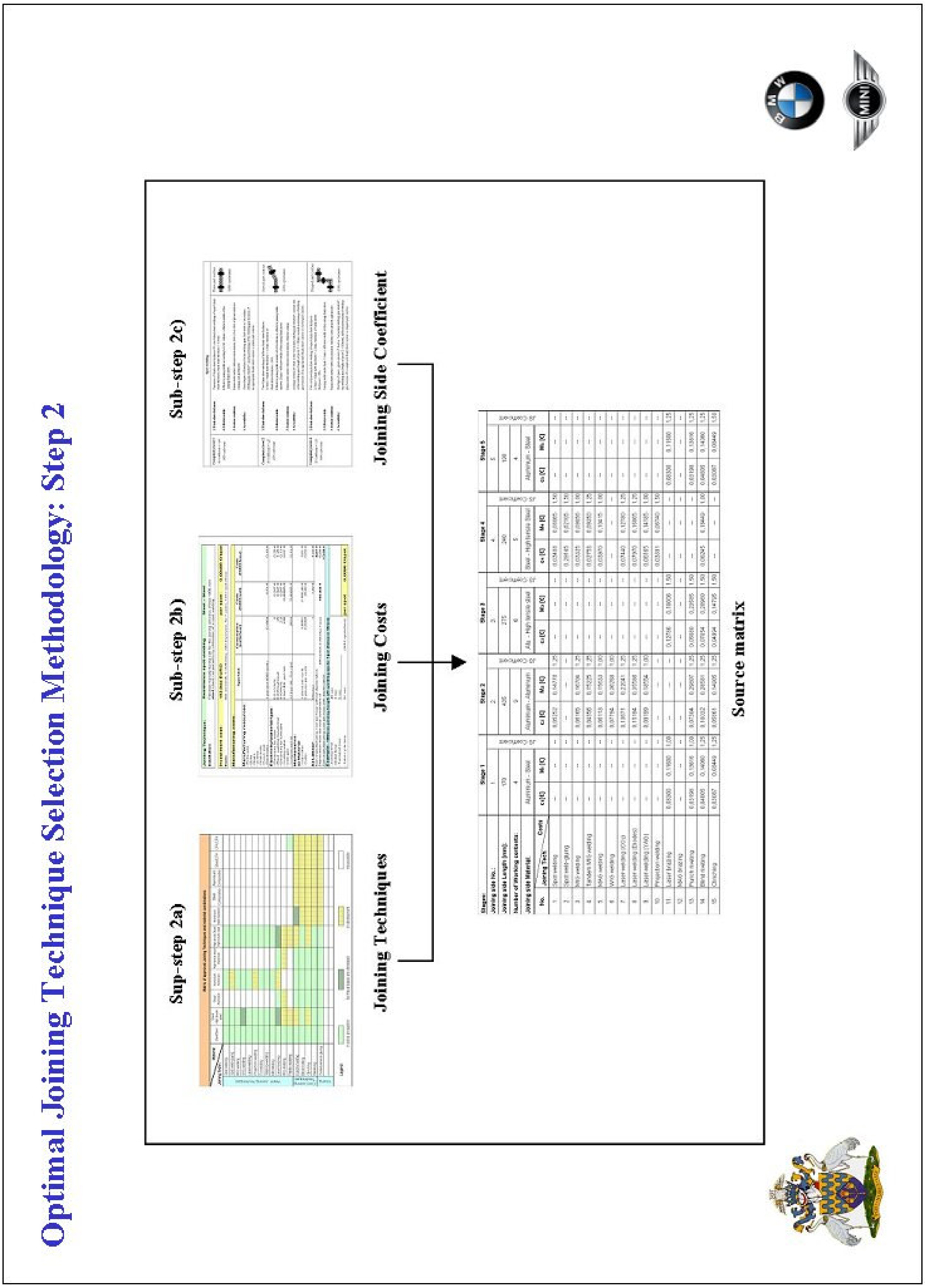


Figure 9.19: Page 19 of the Presentation of the Research Methodology.

Generation of Source Matrix

Stages:		Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Joining side No.:		1		JS Coefficient	2		JS Coefficient	3		JS Coefficient	4		JS Coefficient	5		JS Coefficient	6		JS Coefficient
Joining side Length [mm]:		170			435			275			240			190			250		
Number of Working contents:		4			9			6			5			4			5		
Joining side Material:		Aluminium - Steel			Alu. - Alu.			Alu.-High tensile steel			Steel-High tensile Steel			Aluminium - Steel			Steel - Steel		
No.	Joining Tech. / Costs	c_1 [€]	M_1 [€]		c_2 [€]	M_2 [€]		c_3 [€]	M_3 [€]		c_4 [€]	M_4 [€]		c_5 [€]	M_5 [€]		c_6 [€]	M_6 [€]	
1.	Spot welding	--	--	--	6,56550	18,47250	1,25	--	--	--	5,23200	12,09750	1,50	--	--	--	3,31875	7,10625	1,25
2.	Spot weld-gluing	--	--	--	--	--	--	--	--	--	43,71750	93,15750	1,50	--	--	--	28,66875	61,08750	1,25
3.	MIG welding	--	--	--	7,70625	20,88000	1,25	--	--	--	3,32500	9,85600	1,00	--	--	--	3,92125	10,29750	1,25
4.	Tandem MIG welding	--	--	--	5,44500	19,03163	1,25	--	--	--	3,44750	11,68688	1,25	--	--	--	2,81375	9,75000	1,25
5.	MAG welding	--	--	--	6,11280	15,63300	1,00	--	--	--	3,97000	10,41500	1,00	--	--	--	3,65350	9,82500	1,00
6.	WIG welding	--	--	--	7,79400	36,28800	1,00	--	--	--	--	--	--	--	--	--	4,10900	19,22000	1,00
7.	Laser-welding (CO_2)	--	--	--	17,08875	27,55125	1,25	--	--	--	9,30000	15,97500	1,25	--	--	--	9,11875	14,47500	1,25
8.	Laser-welding (Diodes)	--	--	--	18,99225	44,48250	1,25	--	--	--	9,96250	21,08063	1,25	--	--	--	9,51875	19,71250	1,25
9.	Laser-welding (YAG)	--	--	--	9,19890	18,55440	1,00	--	--	--	6,16500	14,18500	1,00	--	--	--	4,05250	8,37850	1,00
10.	Projection welding	--	--	--	--	--	--	--	--	--	5,08650	10,11000	1,50	--	--	--	4,09063	7,50625	1,25
11.	Laser brazing	8,30000	11,60000	1,00	--	--	--	15,98250	22,50750	1,25	--	--	--	8,30000	11,60000	1,00	12,79375	17,70000	1,25
12.	MAG brazing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3,23000	11,59000	1,00
13.	Punch riveting	3,19760	13,61600	1,00	9,12938	37,25888	1,25	7,62030	35,37810	1,50	--	--	--	3,99700	17,02000	1,25	5,90700	23,33250	1,50
14.	Blind riveting	6,00600	17,57450	1,25	12,54038	35,72663	1,25	10,58040	31,43970	1,50	6,24450	18,44900	1,00	6,00600	17,57450	1,25	8,36025	23,56125	1,50
15.	Clinching	3,85850	10,56100	1,25	7,32600	18,63113	1,25	7,49070	22,19310	1,50	--	--	--	4,63020	12,67320	1,50	5,03400	13,39500	1,50
16.	Flanging	7,64920	12,36520	1,00	21,10950	33,34275	1,25	18,50580	30,78360	1,50	13,07875	21,43375	1,25	9,56150	15,45650	1,25	9,20250	14,51050	1,00
17.	Cohesiveness gluing	6,27055	14,57500	1,25	14,10863	34,99538	1,25	8,88375	21,87300	1,25	7,40313	17,09250	1,25	5,01644	11,66000	1,00	6,96688	14,74563	1,25

Manufacturing cost

Investment cost

Joining Techniques

Figure 9.20: Page 20 of the Presentation of the Research Methodology.

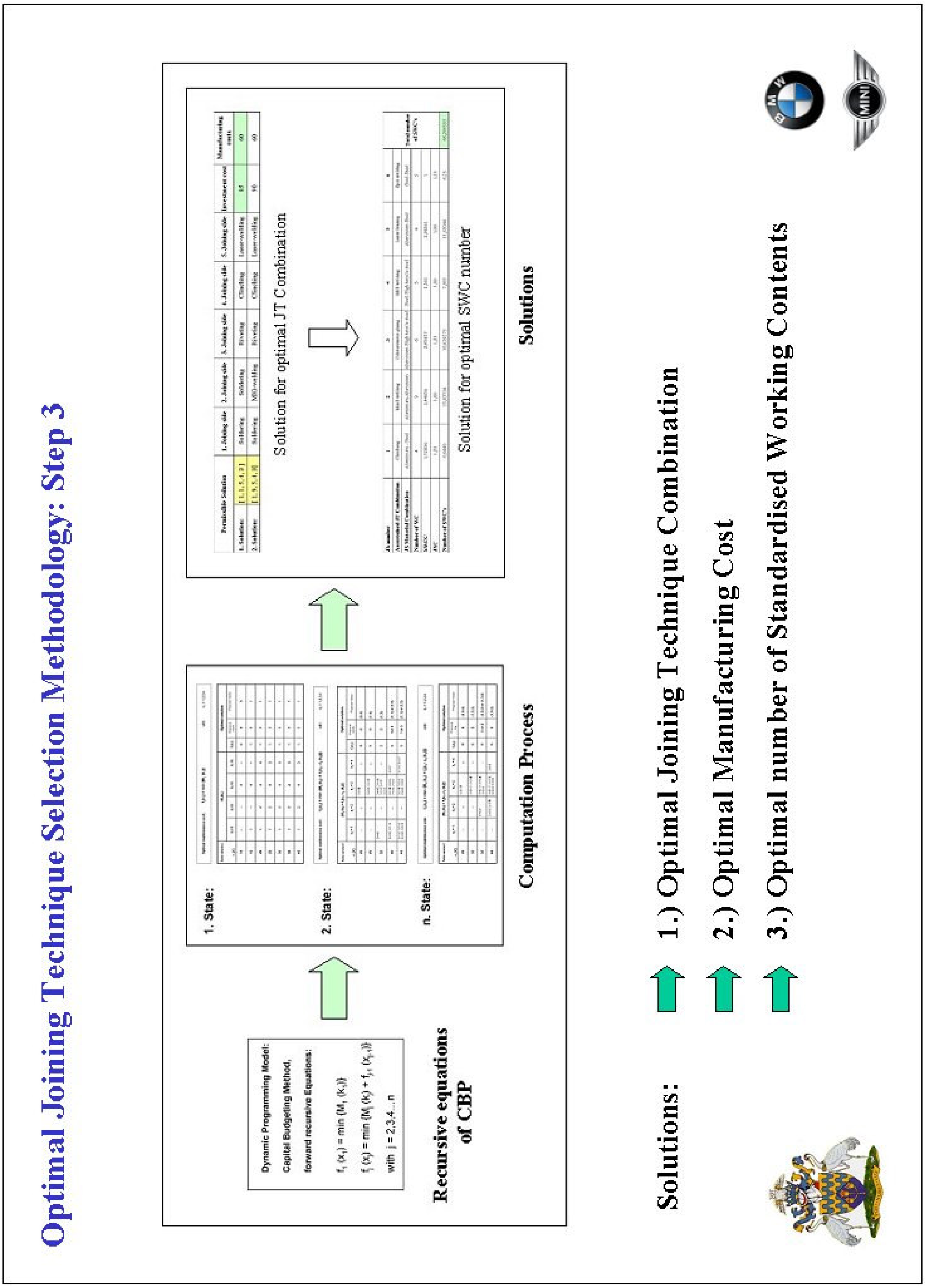


Figure 9.21: Page 21 of the Presentation of the Research Methodology.

Benefits for Design, Planning and Finance Department

Design	Planning	Finance
- The design departments can accomplish an early rough cost estimation for their BIW design concepts. - Feasibility for the early comparison of equivalent BIW design concepts by means of Standardised Working Contents. - Time savings for the design process because of an early and quick cost analysis and forecast.	- Early and intensive contact and data exchange with design and finance departments. - Planning departments obtain early relevant data of the planned time for the calculation of cycle times by means of Working Contents. - Time savings within the planning process because of the short “control loop” systematic. - Because of early planning activities high planning reliability feasible.	- Finance departments obtain as a first approximation an early rough cost estimations of the new BIW design concepts. - Time savings for the finance department due to the fact of short “control loop” systematic. - Data are “bite-sized tailored” for the Finance. - Transparent discussions with BIW engineers by means of Standardised Working Contents.

Figure 9.22: Page 22 of the Presentation of the Research Methodology.

10. Second Questionnaire

10.1 Questions

I. General Questions

Q1: What is your job title?

A1: A 1 = ______________________________

Q2: Which department you are working for?

A2:

- Finance Department ☐
- Planning Department ☐
- Design Department ☐

Q3: For how many years have you been working in that field?

A3:

- ≥ 10 Years ☐
- ≥ 8 Years ☐
- ≥ 6 Years ☐
- ≥ 4 Years ☐
- ≥ 2 Years ☐
- ≥ 1 Year ☐

II. Specific Questions

Q4: Do you expect that the application of Working Content's in connection with the Cost Estimation Methodology will have a positive impact on the collaboration between Design, Planning and Finance?

No impact — Great impact

0% — 25% — 50% — 75% — 100%

A4: A 4= ... %

Additional comment:

- 1 -

Figure 10.1.1: Second questionnaire, page 1.

Q5: Can you rank using a 100%-scale the significance of the calculated results of the methodology in your working area at the Early Phase of the development process?

less significance — high significance

0% 25% 50% 75% 100%

A5: A 5 = ... %

Additional comment:

Q6: Could you indicate the feasibility level of the methodology for a new design concept within the Body-in-White process using the scale below?

low — high

0% 25% 50% 75% 100%

A6: A 6 = ... %

Additional comment:

Q7: Could you asses the usefulness of the methodology for the overall Body-in-White design process by using the following scale?

useless — useful

0% 25% 50% 75% 100%

A7: A 7 = ... %

Additional comment:

- 2 -

Figure 10.1.2: Second questionnaire, page 2.

Q8:

Could you evaluate the usability if the methodology would be implemented in your department?

Usability:

low				high
0%	25%	50%	75%	100%

A8.1:

A 8.1 = ... %

Additional comment:

- 3 -

Figure 10.1.3: Second questionnaire page 3.

10.2. Results of Specific Questions

Question 4: Do you expect that the application of Working Content's in connection with the Cost Estimation Methodology will have a positive impact on the collaboration between Design, Planning and Finance?

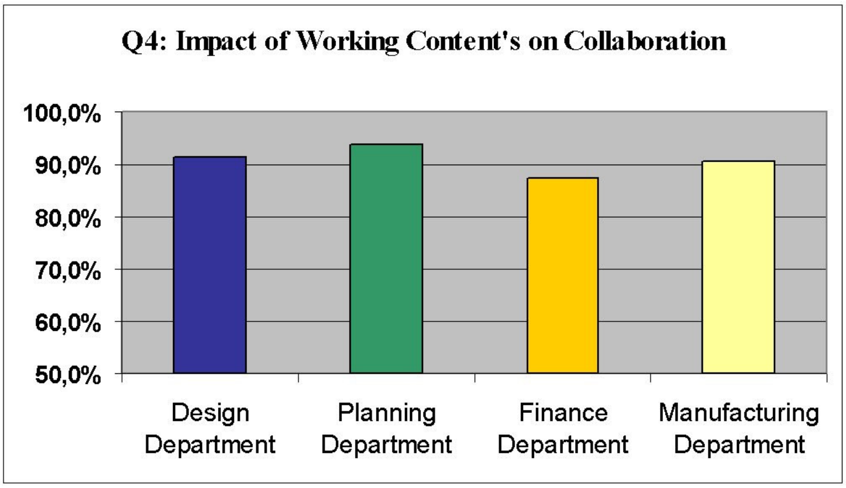


Table 10.2.1: Results of question 4.

Question 5: Can you rank using a 100%-scale the significance of the calculated results of the methodology in your working area at the Early Phase of the development process?

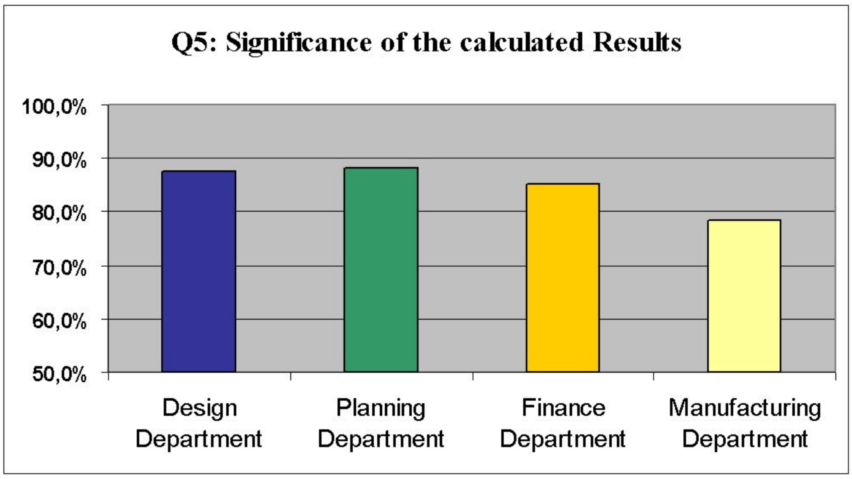


Table 10.2.2: Results of question 5.

Question 6: Could you indicate the feasibility level of the methodology for a new design concept within the Body-in-White process using the scale below?

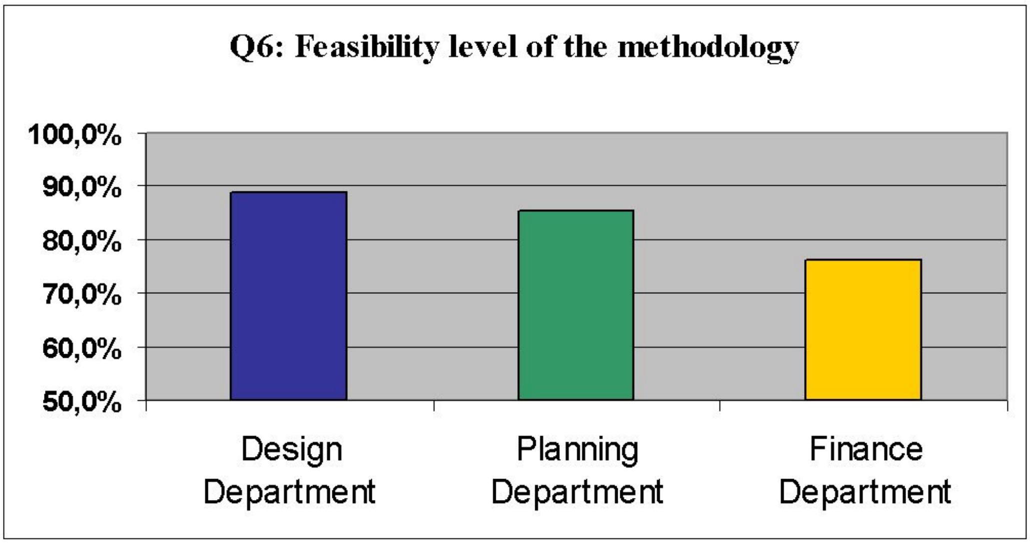


Table 10.2.3: Results of question 6.

Question 7: Could you asses the usefulness of the methodology for the overall Body-in-White design process by using the following scale?

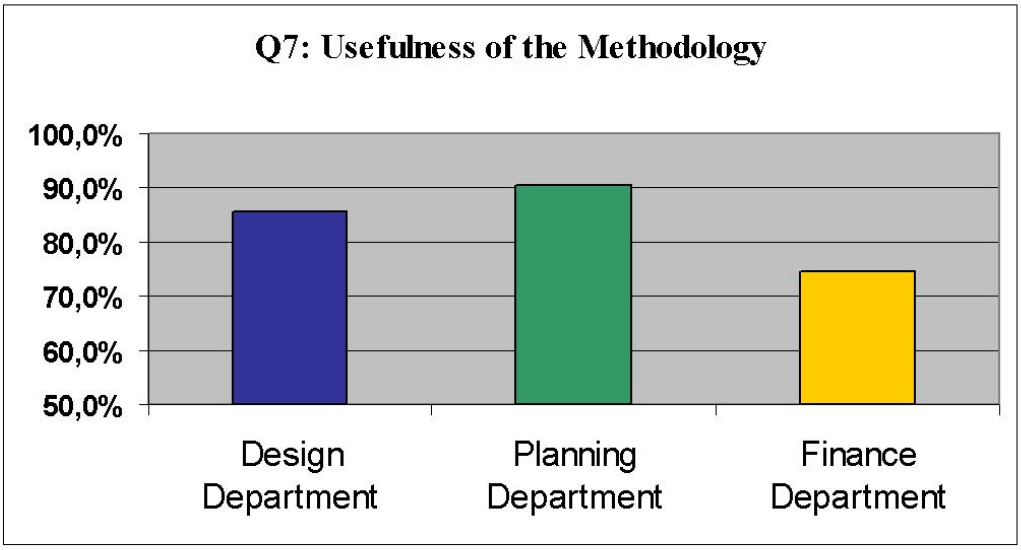


Table 10.2.4: Results of question 7.

Question 8: Could you evaluate the usability if the methodology would be implemented in your department?

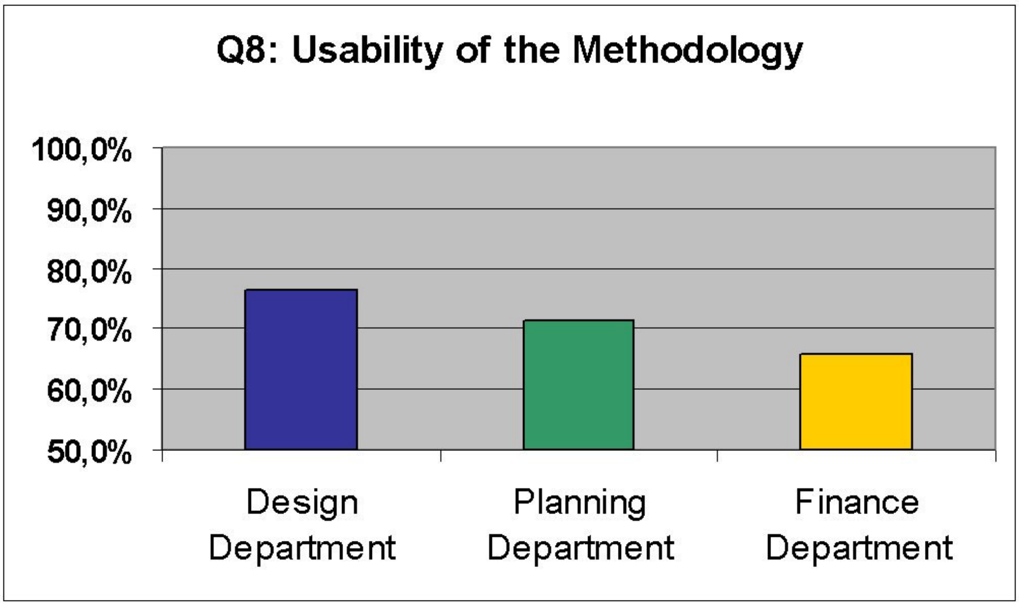


Table 10.2.5: Results of question 8.